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SLCSAT Communication System Design Study

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Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

SLCSAT COMMUNICATION SYSTEM DESIGN STUDY

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ABSTRACT

This report summarizes the results of a Lincoln Laboratory study of issues affecting Submarine Laser Communication Satellite (SLCSAT) implementation. The study compares alternative SLCSAT downlink implementations using semiconductor and solid-state lasers in terms of the satellite transmitter power required to provide a given level of communication service. Signal coding is applied to increase transmitter design flexibility by accommodating a wider range of peak-to-average power trade-offs. Adaptive signaling structures which allow more efficient use of transmitter optical power in the face of channel variations are illustrated. Receiver atomic resonance filter alternatives compatible with operation in solar Fraunhofer lines are discussed. Power efficient tunable transmitter technologies, particularly frequency doubled AlGaAs diode lasers, are found to be very attractive. SLCSAT system size estimates are presented for the various technologies presented. High leverage SLCSAT technology development areas are identified.

A-1

PREFACE

This report summarizes the results of a Lincoln Laboratory study of SLCSAT system design issues and corresponding recommendations. These results were initially presented to U. S. Navy representatives in June 1989.

SLCSAT COMMUNICATION SYSTEM DESIGN STUDY

MIT LINCOLN LABORATORY

21 JUNE 1989

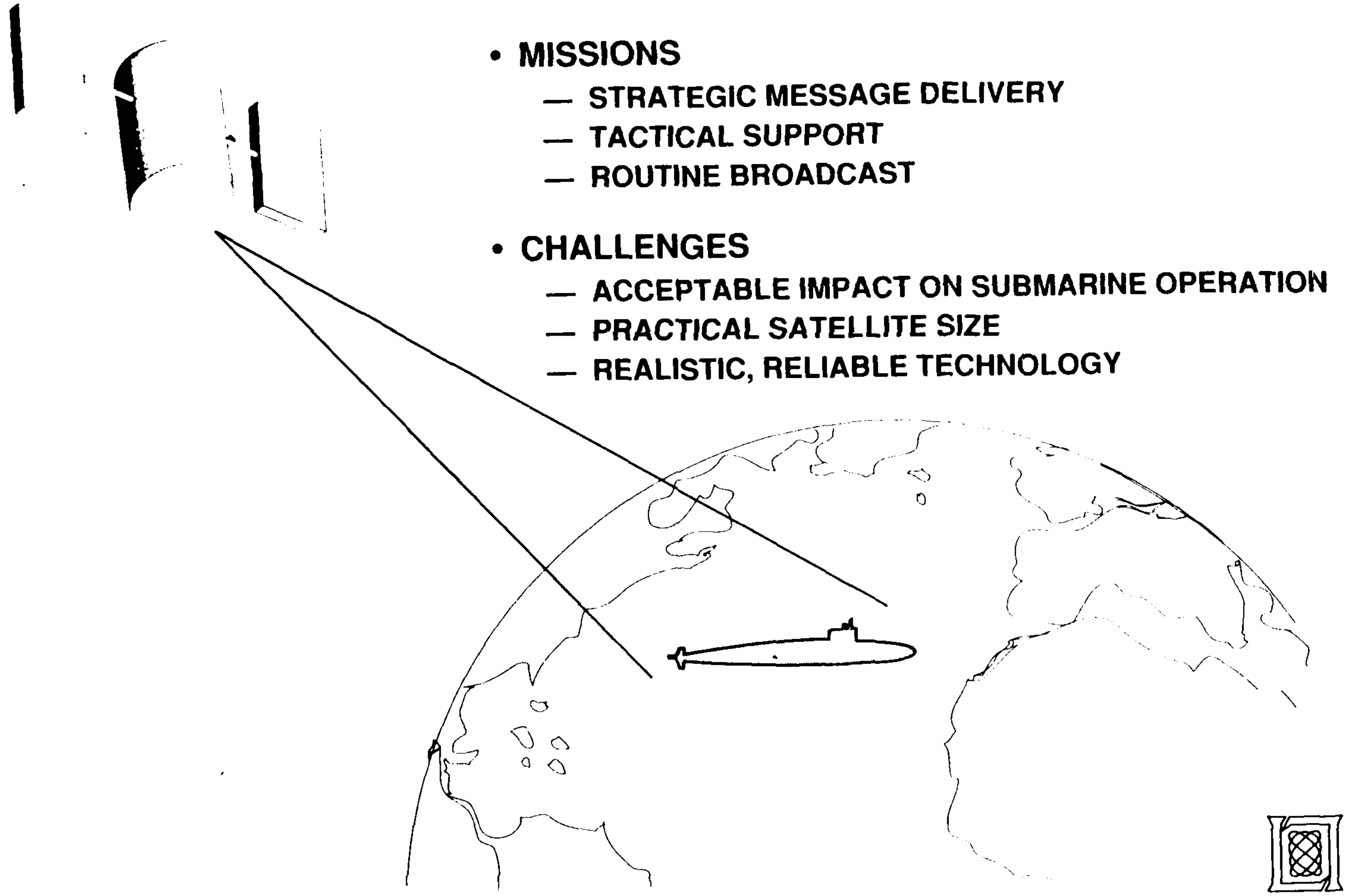
127720-5

Communication to a submerged submarine is one of the most important and difficult to achieve military communication capabilities. In the Submarine Laser Communication Satellite (SLCSAT) concept, optical signals are transmitted in the blue-green region of the spectrum where seawater has relatively low attenuation. Signaling in this transmission window permits less powerful, smaller and less complex transmitters to produce a given received signal level. A communication system for operational submarines must be sufficiently flexible to support a wide variety of missions ranging from strategic command and control, through tactical sea warfare coordination to regular broadcast of information updates.

To be acceptable, a SLCSAT system must support these submarine missions and have an acceptable impact on submarine operations within the limitations of practical satellite size. The use of advanced but realistic technology engineered for reliability is one of the essentials in any practical SLCSAT design.

SLCSAT – SUBMARINE LASER COMMUNICATION BY SATELLITE

- MISSIONS
  - — STRATEGIC MESSAGE DELIVERY
  - — TACTICAL SUPPORT
  - — ROUTINE BROADCAST
- CHALLENGES
  - — ACCEPTABLE IMPACT ON SUBMARINE OPERATION
  - — PRACTICAL SATELLITE SIZE
  - — REALISTIC, RELIABLE TECHNOLOGY



126876-3

This presentation summarizes a recent Lincoln Laboratory study of SLCSAT issues which considered the basic physical and technical issues which determine SLCSAT size. The study identified several advanced technologies which could potentially reduce SLCSAT size if they were fully developed and engineered into practical subsystems.

Prior to describing this study in detail, this presentation will review Lincoln Laboratory experience in submarine communication and summarize current Laboratory optical communication programs.

OUTLINE

- LINCOLN BACKGROUND
- SLCSAT STUDY APPROACH
- SYSTEM ISSUES
  - ORBITS
  - SIGNAL STRUCTURE
  - ADAPTIVE SIGNALING
- WAVELENGTH SELECTION FACTORS
  - SEAWATER ATTENUATION
  - SOLAR BACKGROUND
  - RECEIVER
  - SOURCES
- SYSTEM SIZING
- STUDY CONCLUSIONS AND RECOMMENDATIONS
- DEVELOPMENT PROGRAM

127720-2

Lincoln Laboratory has made significant contributions to the development of submarine communications systems operating in a wide variety of frequency bands.

Lincoln Laboratory led the development of nonlinear signal processing and adaptive modulation and coding technologies for ELF communication to submarines. This development included making both noise and propagation measurements to better quantify the ELF environment. These techniques eventually led to a 20 dB reduction in required transmitter size and were demonstrated in transmissions from the Project Sanguine test transmitter to a Lincoln-built receiver on a submerged SSN. Lincoln work on ELF trailing wire antennas was an important portion of this development.

The Laboratory pioneered development of EHF satellite communication which provides robust Low Probability of Intercept (LPI) communication. Lincoln Experimental Satellites 8 and 9 (LES-8/9) demonstrated an LPI capability for submarine communication in the mid-1970s. Further development of EHF satellite communications technology and systems produced the Lincoln-built FLEETSAT EHF Packages (FEPs) which provide EHF SATCOM for both submarines and ships.

In all these programs, Lincoln worked cooperatively with both Navy laboratories and Navy contractors.

From 1970 to 1972, Lincoln Laboratory performed proof-of-concept level work on a cesium atomic resonant scatter filter for optical communication through scattering media, such as clouds, atmospheric aerosols, and seawater.

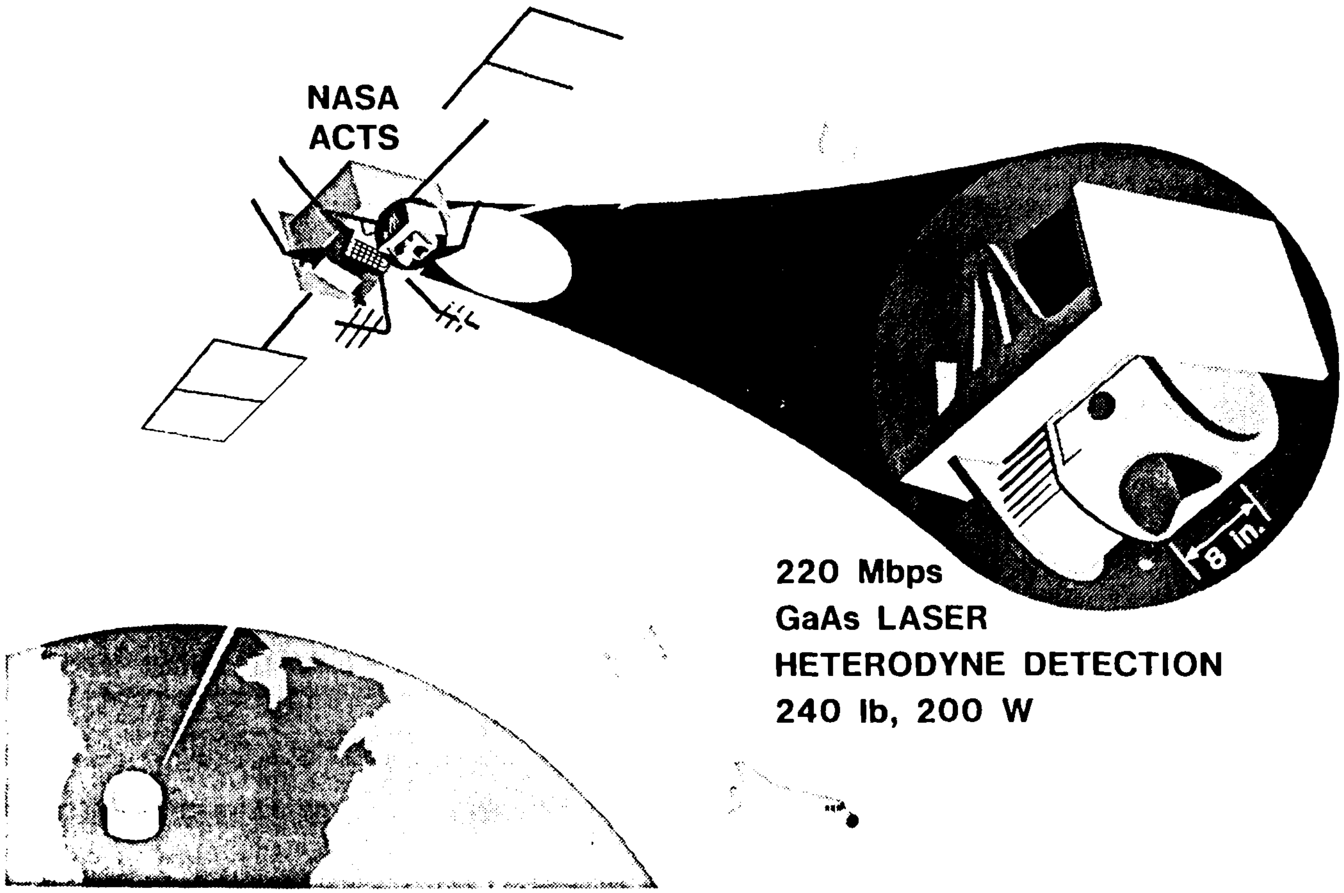
LINCOLN LABORATORY SUBMARINE COMMUNICATION EXPERIENCE

- ELF: PROJECT SANGUINE
  - NON-LINEAR SIGNAL PROCESSING
  - ADAPTIVE MODULATION AND CODING
  - PROPAGATION AND NOISE MEASUREMENTS
  - TRAILING WIRE ANTENNA DEVELOPMENT
  - RECEIVER DEMONSTRATED ON SSN
  - 20 dB REDUCTION IN REQUIRED TRANSMITTER POWER
- VLF: NOISE PROCESSING AND CODING
- UHF: TRAILING WIRE ANTENNA
- EHF SATCOM
  - LPI SIGNAL DESIGN
  - LES 8/9 DEMONSTRATION
  - FEP DESIGN, FABRICATION AND OPERATION
  - WORKED COOPERATIVELY WITH NAVY LABORATORIES AND CONTRACTORS
- LASER: SUBMARINE COMMUNICATION
  - Cs RESONANT SCATTER FILTER DEVELOPMENT (1970-1972)

126881-3

Lincoln Laboratory began developing heterodyne optical communication technology for satellite crosslinks in 1980. Following this initial development, the Air Force requested that the Laboratory demonstrate this technology in space. In response to this request, Lincoln designed the Laser Intersatellite Transmission Experiment (LITE) package to be flown as a communication experiment on the NASA Advanced Communication Technology Satellite (ACTS). The LITE package was designed to demonstrate the feasibility of optical crosslinks by using the technology to transmit data from the ACTS satellite to an optical receiver at an astronomical site. In the LITE system, heterodyne detection was used to allow synchronous range communication at data rates up to 220 MB/s with a simple 30 mW AlGaAs laser diode as the transmitter. The LITE design was completed and being fabricated when Air Force budgetary constraints forced cancellation of the flight program.

LITE PACKAGE



119427-3

The Air Force requested that Lincoln build a LITE engineering model to validate the flight worthiness of the LITE design even though budgetary constraints could not support the flight experiment. The LITE optical module is being built from the design developed for the ACTS flight experiment. The LITE engineering model will be tested to verify acquisition, tracking, and communication performance after exposure to flight-level environmental tests. Other tests will also verify that the LITE system can accurately point its very narrow transmit and receive beams despite spacecraft micromotion produced by motion in momentum wheels, solar panels, etc. Successful fabrication and testing of this flight design optical module will reduce risk for future optical crosslink systems.

LASER INTERSATELLITE TRANSMISSION EXPERIMENT (LITE) ENGINEERING MODEL

KEY ISSUES

- MECHANICAL/THERMAL STRESSES
- POINTING & SPATIAL ACQUISITION
- PLATFORM JITTER

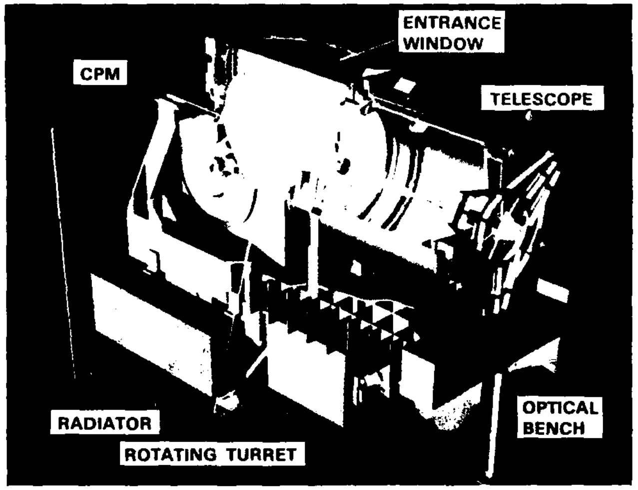
APPROACH

- FLIGHT DESIGN OF OPTICAL MODULE
- MECHANICAL/THERMAL TESTING
- FULL FUNCTIONAL TESTING
- SIMULATED SPACECRAFT MICROMOTION

RESULT

- REDUCED RISK FOR OPERATIONAL SYSTEM

LITE OPTICAL MODULE

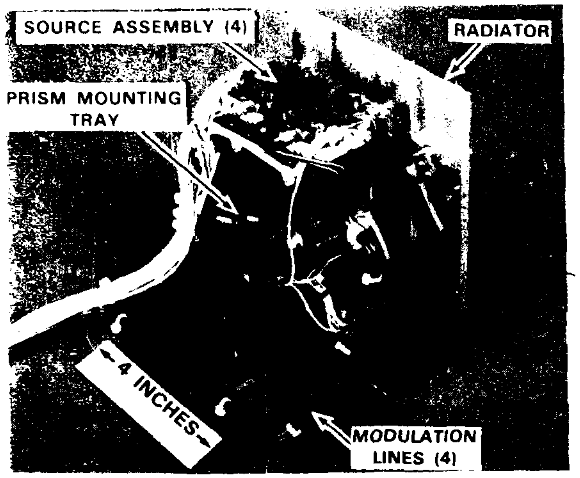


122832-2

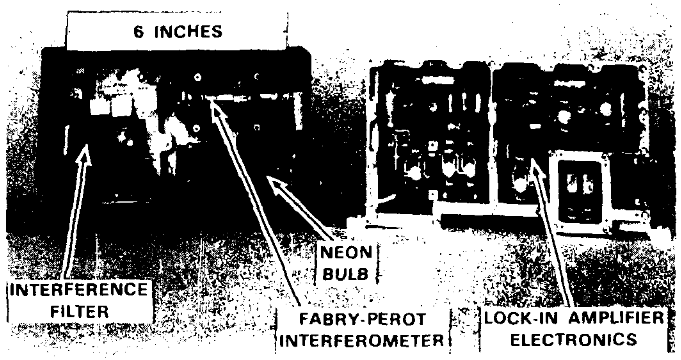
Lincoln Laboratory has completely designed and built several subsystems for the LITE engineering model. The laser transmitter provides the mechanical, electrical, and optical environment for the 30 mW AlGaAs laser diode transmitters. The critical component of this transmitter, the source assembly module, has already passed qualification level vibration and thermal tests with no performance degradation. The laser diagnostic module provides the optical and electronic capabilities required to set LITE transmitter frequency, FSK tone spacing and power. The accuracy of this system allows link acquisition to occur in seconds and limits performance losses from frequency and *tone spacing errors* to a few tenths of a dB. Critical subassemblies of the diagnostic module have already passed qualification tests. Flight qualification tests of the completed transmitter and diagnostic assemblies will completed in the fall of 1989.

LASERCOM FLIGHT SUBSYSTEMS

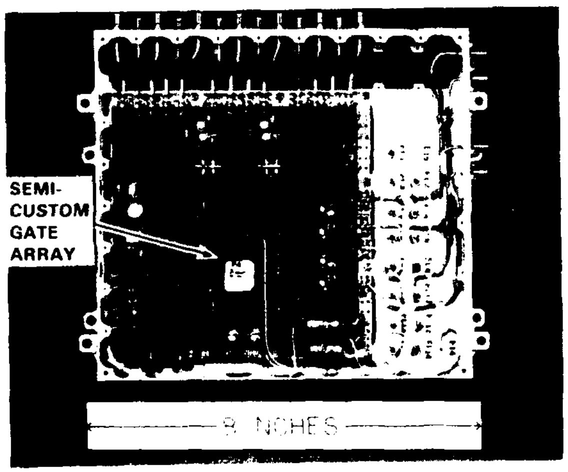
30 mW LASER TRANSMITTER



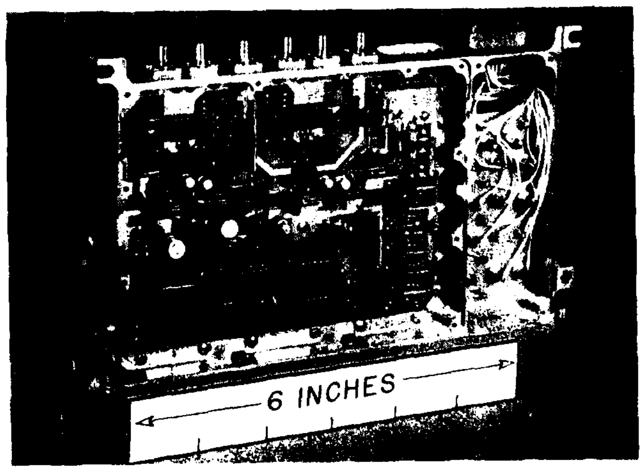
LASER DIAGNOSTICS MODULE



220 Mbps DATA FORMATTER



LASER FSK MODULATOR

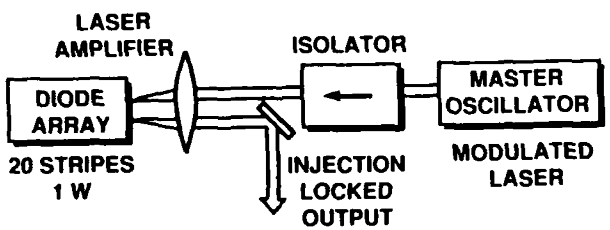


122632-1

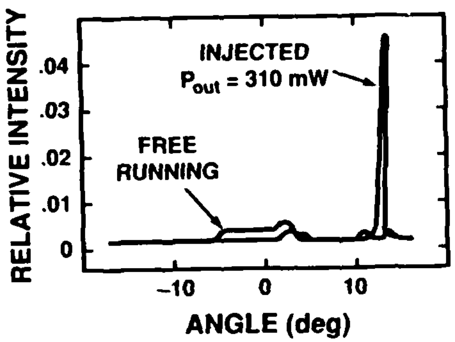
Lincoln Laboratory is also working to extend LASERCOM technology to increase future system capabilities while simplifying system design with reduced aperture size. Higher power, efficient, single-mode laser diode transmitters are one of these key technology extension areas. Development efforts are under way on two different approaches; namely, injection-locked power amplifiers and nonlinear optics, to obtaining significantly higher device module powers for heterodyne optical communication. Lincoln Laboratory has injection-locked a 1 Watt laser diode array to a heterodyne laser communication signal and obtained 310 milliwatts of injection-locked power. The injection-locked output was a sufficiently accurate version of the injected "master oscillator" communication signal that there were no observable degradations in receiver performance thresholds. In a nonlinear optical power combining experiment, Lincoln Laboratory demonstrated that two separate, equal power, temporally coherent optical beams could be combined into a single beam with more than 95 percent of the total power in the single beam. This combining technology allows the outputs of several injection-locked arrays to be combined into a single beam for frequency doubling and transmission. These increased laser diode device module powers are an important technology development which could substantially reduce SLCSAT size.

LASERCOM TECHNOLOGY EXTENSION
APPROACHES TO HIGH POWER

MASTER OSCILLATOR/POWER AMPLIFIER

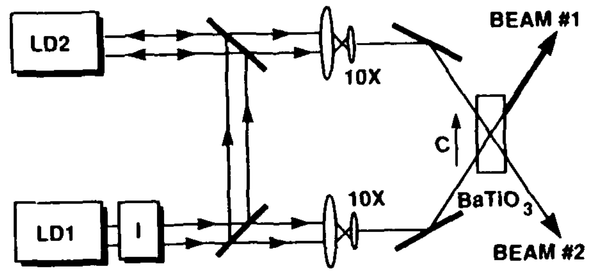


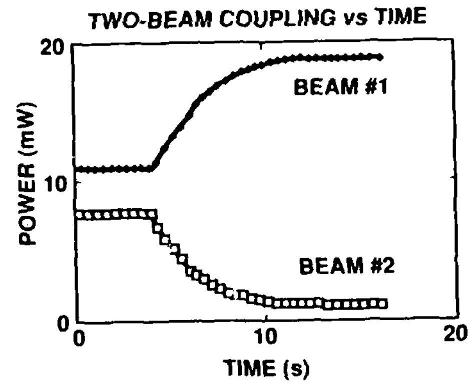
ARRAY FAR FIELD INTENSITY DISTRIBUTION



- 310 mW SINGLE FREQUENCY/SPATIAL MODE DEMONSTRATED
- NO OBSERVED MODULATION DEGRADATION
- AMPLIFICATION OF MULTIPLE CHANNELS POSSIBLE

NON-LINEAR OPTICAL POWER COMBINING





- NEARLY COMPLETE POWER TRANSFER DEMONSTRATED
- INSENSITIVE TO SLOW ALIGNMENT CHANGES
- COMBINATION OF HIGH POWER ARRAYS POSSIBLE

124328-2

Lincoln's approach to implementing a SLCSAT system is to use the technologies which provide a specific SLCSAT capability in the smallest, least complex satellite. Using this approach, a baseline SLCSAT capability is described in terms of the data rates, coverage areas, orbital constellations, etc., required to provide a specific communication capability. Then using the baseline capability as a reference point, alternative SLCSAT system approaches can be compared in terms of the system size required to achieve a given communication capability with specific transmitter and receiver technologies and channel characteristics for each wavelength.

This study brought together several key technologies which offer the potential of reducing SLCSAT system size and complexity. Error control coding as part of the SLCSAT modulation allows significant reductions of transmitter peak power requirements and permits use of a wider range of transmitter technologies with differing peak/average power trade-offs. Adaptive signaling formats can save average transmitter power by allowing the transmitter to direct its energy more efficiently by sending less energy to areas where channel conditions require less signal energy. Semiconductor lasers and solid state crystalline lasers allow more efficient power generation than other laser technologies such as the chemical laser. These more efficient semiconductor and solid state laser technologies require less satellite power and hence a less complex transmitter satellite while also providing necessary reliability and tunability. Finally, narrower band atomic resonance filters (ARFs) reject larger amounts of solar background energy and thus reduce required signal levels. Operating an efficient narrowband ARF at a wavelength matched to one of the Fraunhofer dips in the solar background offers the potential of further decreasing system size.

LINCOLN SLCSAT APPROACH

- EXAMINE MESSAGE RATE, AREA, DEPTH, ORBIT AND IMPLEMENTATION TRADE-OFFS
- EMPLOY TECHNOLOGIES THAT REDUCE SATELLITE SIZE AND COMPLEXITY
- CHOOSE WAVELENGTH WHICH BEST MATCHES RECEIVER AND TRANSMITTER TECHNOLOGIES TO CHANNEL CHARACTERISTICS

KEY TECHNOLOGIES

- CODING TO REDUCE PEAK POWER REQUIREMENTS
- ADAPTIVE SIGNAL FORMATS MATCHED TO CHANNEL CONDITIONS TO REDUCE AVERAGE POWER REQUIREMENTS
- SEMICONDUCTOR AND SOLID STATE LASER SOURCES FOR EFFICIENCY, RELIABILITY AND TUNABILITY
- NARROWBAND ATOMIC RESONANCE FILTERS (ARFs) MATCHED TO FRAUNHOFER DIPS IN SOLAR BACKGROUND

127379-1

Incorporation of these techniques into a SLCSAT system would significantly reduce peak and average transmitter power requirements to the extent that SLCSAT systems using multiple low power semiconductor or solid state transmitter modules appear feasible. Semiconductor laser based systems are particularly attractive because of their higher power efficiency.

If these advanced technologies are to be used in a practical size SLCSAT system, they must be further developed and then carefully engineered into a complete system design. This SLCSAT system design and engineering will also require accurate channel models developed from an expended and systematic measurement program.

SUMMARY OF LINCOLN SLCSAT STUDY CONCLUSIONS

- THERE ARE TECHNIQUES WHICH SIGNIFICANTLY REDUCE PEAK OPTICAL AND AVERAGE SATELLITE PRIME POWER REQUIREMENTS
- SYSTEMS USING MULTIPLE LOW POWER SEMICONDUCTOR OR SOLID-STATE TRANSMITTER MODULES APPEAR TO BE PRACTICAL
- SEMICONDUCTOR BASED SYSTEMS PARTICULARLY DESIRABLE
- HIGH ALTITUDE ORBITS ARE PREFERRED
- TECHNOLOGY DEVELOPMENT AND CHANNEL MEASUREMENT PROGRAMS RECOMMENDED

130955-1

A fixed performance goal must be used when comparing the size of different system alternatives. Although there are no firm formal "requirements" for a SLCSAT system, previous studies suggest a broad range from strategic command and control, through tactical sea warfare coordination to routine broadcast. This study used a baseline message delivery area requirement of 10^8 bits-square miles/hour during a cloudy day. *With adaptive signaling*, this capacity can be used in many ways to support various missions with different mixes of message length, coverage area, and delivery time. Although submarine receiver depth is treated as a parameter, the performance baseline assumed 100 meter receiver depth. The signal formats selected for evaluating the various alternatives were chosen to allow adaptation strategies which can shorten delivery times when conditions are better then those assumed for system sizing.

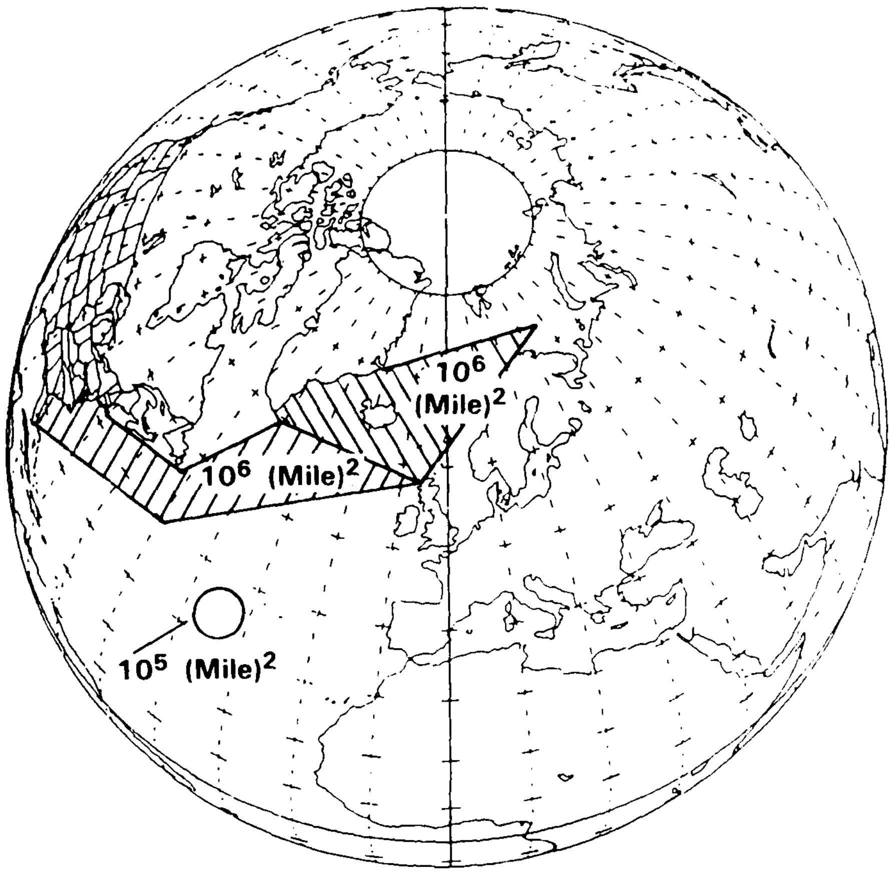
SYSTEM PERFORMANCE GOALS

- NO FIRM REQUIREMENTS
- PREVIOUS STUDIES SUGGEST THREE TYPES OF SERVICE:
  - BASIC CONNECTIVITY
    - ONCE PER HOUR BROADCAST OF SHORT MESSAGE TO WIDE AREA
  - SPECIAL DELIVERY
    - TACTICAL SUPPORT
    - KNOWN GENERAL AREA
    - FEW MINUTES DELIVERY
  - ROUTINE
    - NOT TIME URGENT, CAN BE AT NIGHT
- MESSAGE DELIVERY BASELINE WITH 1000 BPS SPOT RATE: 10^8 BITS $\times$ MILES^2/HOUR e.g.,
  - 100 BIT MESSAGE TO 10^6 MILES^2 IN 1 HOUR
  - 100 BIT MESSAGE TO 10^5 MILES^2 IN 6 MINUTES
  - 5000 BIT MESSAGE TO 50 MILE DIAMETER CIRCLE IN 6 MINUTES
- DELIVER TO >100 m DEPTH UNDER CLOUDY DAYTIME CONDITIONS
- SHORTEN DELIVERY TIME IF CONDITIONS PERMIT

130806-7

The map illustrates the size of areas which could be covered by a system with this baseline capability operating in a manner which uses the 10^8 bits-square miles/hour to deliver a 100 bit message *to all users in a 10^6 square mile area* in one hour. The map also shows a 10^5 square mile area which could be covered with a 100 bit message in 6 minutes with the baseline capability.

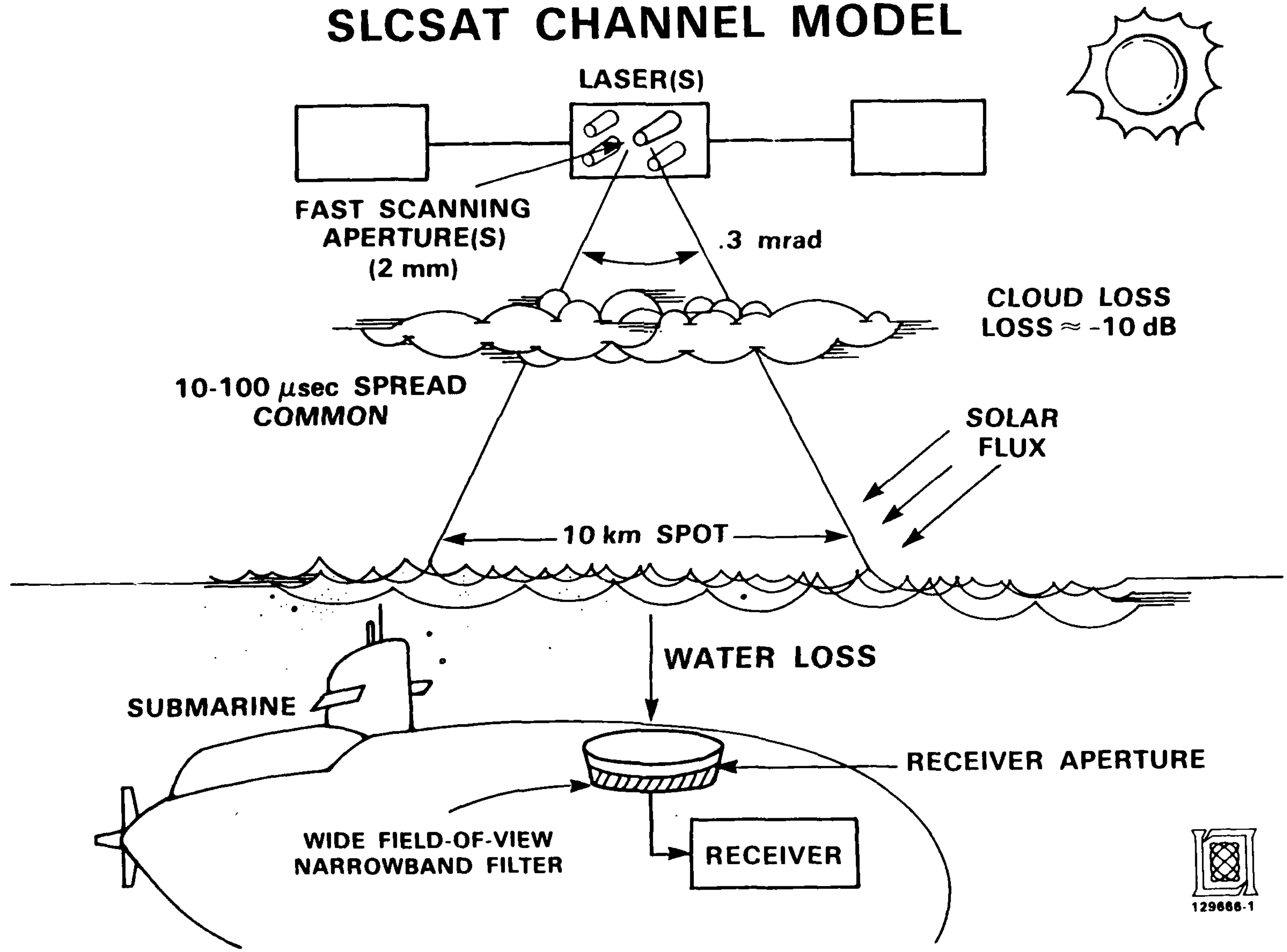
VIEW OF EARTH FROM 22,300 MILE ALTITUDE, 63° LAT, 0° LON



127336-4

The sketch illustrates the major channel effects which must be included in the SLCSAT link calculation underlying any system size comparison. The issues of receiver aperture, filter bandwidth, and water losses will be covered later in this presentation. Although clouds are not always present in the SLCSAT signal propagation path, clouds occur a sufficiently large fraction of the time that an operationally useful SLCSAT system must be able to operate when clouds are present. Spatial and temporal signal spreading in the clouds effectively limits the spot size and pulse lengths which can be used. A 10 km diameter spot on the ocean surface was used as the instantaneous coverage area of the scanning transmitter beam. Since this spot size is comparable to cloud induced spatial spreading there is little extra spatial spreading loss from clouds beyond the normal back scatter loss which equally attenuates both signal and background light (typically 10 dB or less). *Even for the highest altitude* satellites, e.g. synchronous, this spot size requires very modest transmit apertures of 2 millimeters or less to achieve the required optical beamwidths. The extent of temporal spreading in a SLCSAT signal is a strong function of cloud cover "thickness." Depending upon the required availability and thus upon the severity of the cloud cover, cloud induced pulse spreading of 10-100 microseconds must be accommodated. Although somewhat smaller pulse spreading and lower back scatter losses occur in some climate areas, the link sizing in this study assumed a conservative 100 microsecond pulse spreading and 10 dB loss during cloudy operation.

SLCSAT CHANNEL MODEL



We will briefly discuss the overall system design issues of orbit selection, signal structure, and adaptive signaling before addressing wavelength selection and the accompanying issues of receiver and transmitter technology.

OUTLINE

- LINCOLN BACKGROUND
- SLCSAT STUDY APPROACH
- SYSTEM ISSUES
  - ORBITS
  - SIGNAL STRUCTURE
  - ADAPTIVE SIGNALING
- WAVELENGTH SELECTION FACTORS
  - SEAWATER ATTENUATION
  - SOLAR BACKGROUND
  - RECEIVER
  - SOURCES
- SYSTEM SIZING
- STUDY CONCLUSIONS AND RECOMMENDATIONS
- DEVELOPMENT PROGRAM

127720-2

A number of issues must be addressed in selecting a satellite constellation to provide a specified capability. System cost is driven by both the number and the size of the satellites required. The number of satellites and their orbits determine the fraction of time that some satellite is in position to service users in a specific operational area. Satellite and receiver motion produce Doppler shift in the signal light. The magnitude of this Doppler shift varies with orbit and orbital position. Since a practical ARF is essentially a fixed frequency filter, the transmitter must precorrect for any Doppler which would move signal energy outside the ARF detection band. The system designer must also account for the complexity of connecting each transmitter satellite to a communication master station. The impact of providing this connectivity can be significant for low altitude systems in which satellites are often outside the field of view of any existing ground station.

Three other issues also significantly impact transmitter and satellite constellation sizing. First, for the 10 km diameter active spot size, the transmitter power required to produce a given signal level is essentially independent of altitude. Second, the aperture required to produce the beam width even from high altitude is so small that the entire downlink transmitter system (transmitter plus optics) size is nearly independent of satellite altitude. Third, since grazing angles below 20° imply additional losses of several dB, especially with clouds, use of low grazing angles should be avoided in an efficient SLCSAT.

SLCSAT ORBIT CHOICE

- TRADEOFF ISSUES
  - AVAILABILITY AND VISIBILITY OF SPECIFIC AREAS
  - COVERAGE AREA vs TIME
  - NUMBER AND SIZE OF SATELLITES
  - TRANSMITTER/APERTURE SIZE
  - DOPPLER PRE-CORRECTION REQUIREMENTS
  - CONNECTIVITY TO MASTER STATIONS

- TRANSMITTER SIZING
  - APERTURE FOR 10 km TRANSMIT SPOT LESS THAN A FEW MILLIMETERS
  - DOWNLINK TRANSMITTER POWER NEARLY INDEPENDENT OF ALTITUDE
  - GRAZING ANGLES BELOW 20° IMPLY LARGE ADDITIONAL LOSSES ESPECIALLY WITH CLOUDS

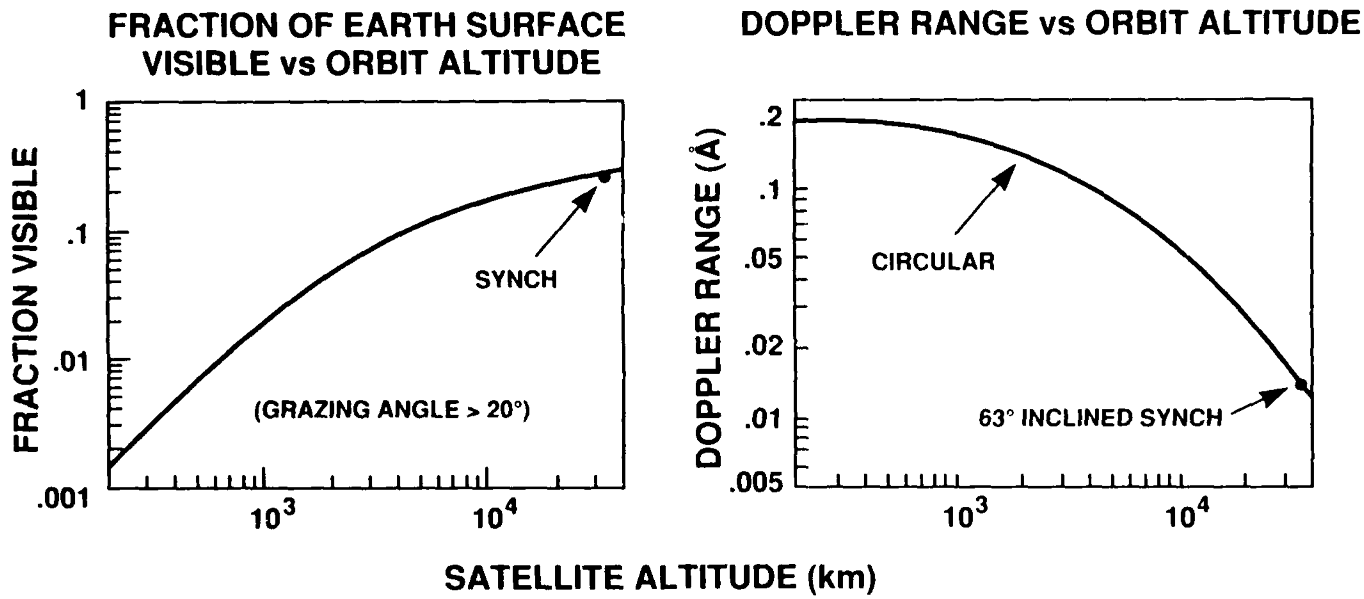
127336-9

The graph showing the fraction of the earth surface visible with grazing angles above 20^{o} indicates that many low altitude satellites will be required to assure timely access to a specific operational area because each satellite at low altitude instantaneously sees such a small percentage of earth's surface. Low altitude also limits adaptation flexibility since each satellite sees a small, relatively local, portion of the earth's surface and thus is less likely to see the mixtures of clear and cloudy areas and the mixtures of seawater types necessary for obtaining improved performance with adaptive signaling.

The graph of Doppler range versus orbit altitude shows that Doppler correction is of a much smaller magnitude at higher altitude orbits and thus that Doppler correction is a less demanding problem for a high altitude SLCSAT system. As will be discussed later, ARF absorption bands can be somewhat narrower than 0.01 Angstrom. For these narrowband ARFs, some pretuning for Doppler is required for all but geosynchronous satellites (0^{o} inclined synchronous) which do not give high latitude coverage.

These factors plus the relative independence of transmitter size and satellite altitude lead us to recommend high altitude orbits for a SLCSAT downlink system.

ORBIT SELECTION ISSUES



- LOW ALTITUDES REQUIRE MANY SATELLITES TO ASSURE TIMELY DELIVERY
- HIGH ALTITUDE ORBITS HAVE MUCH SMALLER DOPPLER RANGE
- REQUIRED TRANSMITTER POWER NEARLY INDEPENDENT OF ALTITUDE
- HIGH ALTITUDE ORBITS RECOMMENDED

127721-1

The graph shows the values of peak and average power required to achieve the same communication capacity with and without coding for daylight operation with M-ary pulse position modulation (PPM) with various M values. The lower peak power requirements for coded operation and the wider range of the peak power/average power trade-off curve illustrate the use of coding to reduce peak power requirements. This flexibility allows the communication system engineer to accommodate a wider range of transmitters with different peak/average power capabilities by adapting the modulation to transmitter characteristics. The shaded area illustrates the range of peak and average power capabilities for a conservatively sized near term transmitter module with limited pulse rate. The parameter values used for this example are typical of those for a frequency doubled Nd:BEL laser transmitter operating at 535 nm.

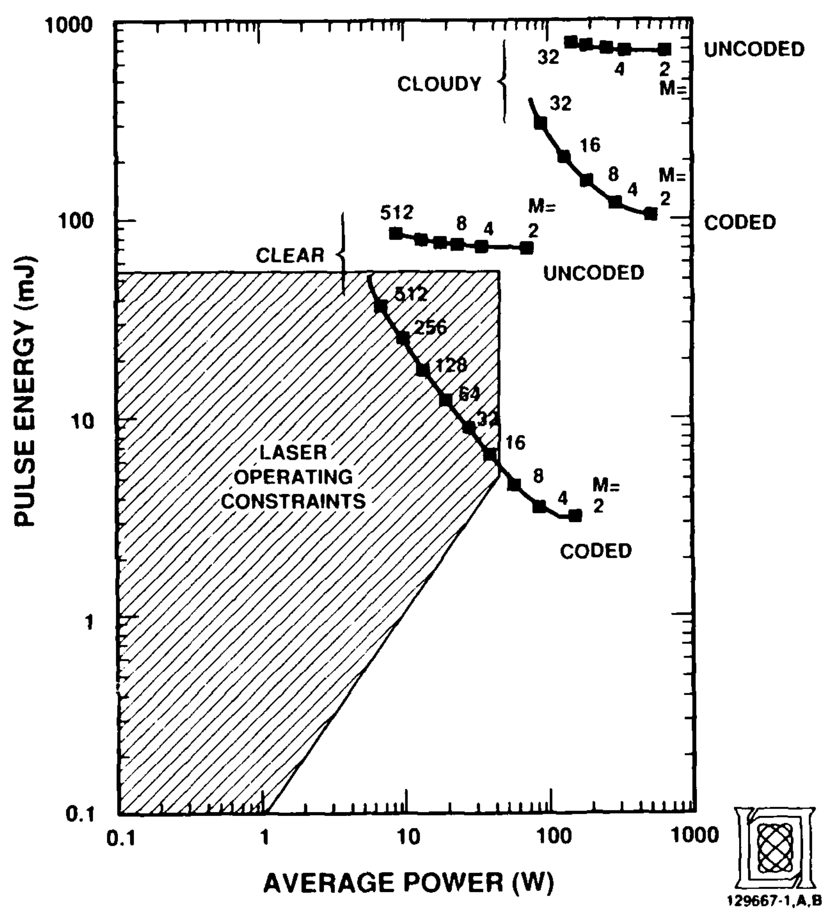
MATCHING MODULATION / CODING TO LASER TRANSMITTER

- CODED M-ARY PPM
  - –REDUCES PEAK POWER (Pulse energy)
  - –CAN MATCH LASER PEAK AND AVERAGE POWER CONSTRAINTS
  - –CAN USE WITH ADAPTIVE SIGNAL PROCESSING TO MATCH CHANNEL
  - –VERY LOW ERROR RATE ABOVE SNR THRESHOLD

EXAMPLE :

DAYTIME OPERATION
RATE = 1000 bps
Nd:BEL LASER
100 m TYPE II WATER
6 dB SIGNAL MARGIN
PULSE DURATION :
10μs CLEAR
100μs CLOUDY

ENERGY-POWER TRADE-OFF EXAMPLE

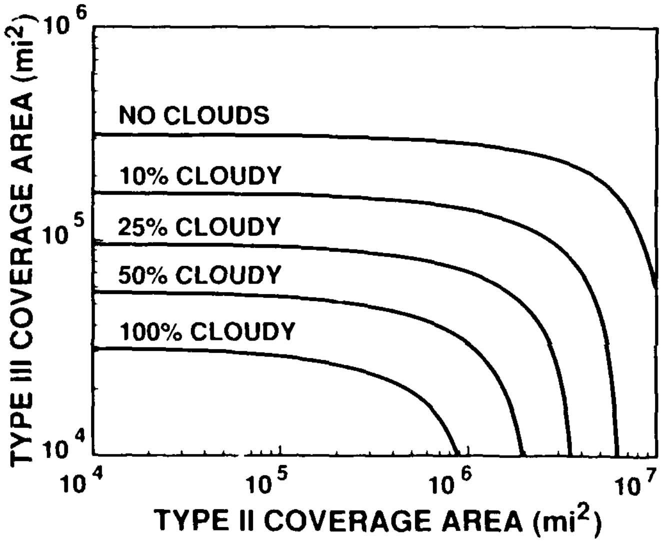


The graph shows combinations of the areas of Type II and Type III waters which can be covered with an adaptive system for various percentages of cloud cover in the coverage areas. In addition to allowing most efficient use of transmitter power, an adaptive system decreases system sensitivity to channel modeling details by allowing changes in operating parameters to accommodate channel model refinements. A well designed SLCSAT system could vary several different parameters to adapt to channel conditions without excessively disturbing the hardware operating envelope. The time a transmitter beam illuminates a specific area can be varied *a priori* to account for different water types and depths and varied dynamicly to account for cloud and day/night conditions. Similarly, multiple transmit beams from separate transmitter modules may be combined or independently pointed to accommodate such variations. The signal format may also be varied to accommodate changes in cloud cover by varying the length of M-ary PPM signal time slots with corresponding changes in symbol rate or in the value of M. For transmitters which inherently produce very short pulses, the receiver may also adapt to channel conditions by narrowing its time gate during less than worst case cloud conditions.

ADAPTIVE SIGNALLING TECHNIQUES MATCH WATER AND ATMOSPHERIC CONDITIONS

- MAKE MOST EFFICIENT USE OF TRANSMITTER POWER
- DECREASE SENSITIVITY TO CHANNEL MODEL DETAILS
- VARIABLE PARAMETERS
  - — BEAM DWELL TIME
  - — SIGNAL FORMAT
  - — RECEIVER TIME GATE
  - — MULTIPLE BEAM POINTING

ADAPTATION EXAMPLE: AREA COVERED IN 1 HOUR FOR 100 BIT MESSAGE TO 100 m DEPTH



127721-2

An adaptive signal structure incorporating coding can reduce SLCSAT system size and complexity in two ways. First, coding reduces peak power requirements and accommodates a wide range of peak and average power capabilities. Second, adaptive signaling allows more efficient use of available transmitter power by varying the signal structure to match a wider variety of both static and dynamic channel conditions.

SIGNAL DESIGN SUMMARY

- USE CODING TO
  - MATCH TRANSMITTER PEAK/AVERAGE POWER CHARACTERISTICS
  - REDUCE REQUIRED ENERGY PER PULSE (Up to 15 dB)
- USE ADAPTIVE SIGNAL STRUCTURE TO
  - MATCH CHANNEL CHARACTERISTICS
  - MAKE MOST EFFICIENT USE OF TRANSMITTER POWER AVAILABLE

127720-7

Lincoln's approach to selecting a SLCSAT system wavelength is to select the operating wavelength which produces the smallest system after accounting for transmitter and receiver capabilities in combination with seawater attenuation and solar background levels.

OUTLINE

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- SYSTEM SIZING
- STUDY CONCLUSIONS AND RECOMMENDATIONS
- DEVELOPMENT PROGRAM

127720-2

The chart summarizes the issues which a SLCSAT system engineer must consider in selecting the wavelength for an efficient system. The seawater loss to a given depth is dependent both upon wavelength and water type. The top section of the figure shows the variation of seawater attenuation to 100 meter depth as a function of wavelength and seawater type using Jerlov water types with the Austin depth projection[1]. The next section of the figure illustrates the spectral fine structure in solar background resulting from Fraunhofer absorption lines. A SLCSAT system operating at one of these low solar background wavelengths could potentially use a smaller transmitter because of the locally lower background level. The next section of the chart shows the operating wavelength of several known atomic resonance filters and indicates that ARFs have not been developed at most wavelengths corresponding to Fraunhofer dips in the solar background. The bottom section of the chart shows operating wavelength ranges for several well-known SLCSAT candidate laser systems as well as the operating ranges for some tunable laser options. The wide tunability of either the diode laser systems (AlGaAs and strained layer, e.g., InGaAs/GaAs) or the tunable solid state laser systems (Ti:sapphire and Cr-based) can be exploited by the SLCSAT system engineer to provide a transmitter matched to a specific wavelength where an efficient narrowband ARF exists in combination with relatively good seawater properties and relatively low solar background. The higher dc to optical efficiency of the diode laser systems makes them especially attractive in terms of required transmitter satellite power and weight.

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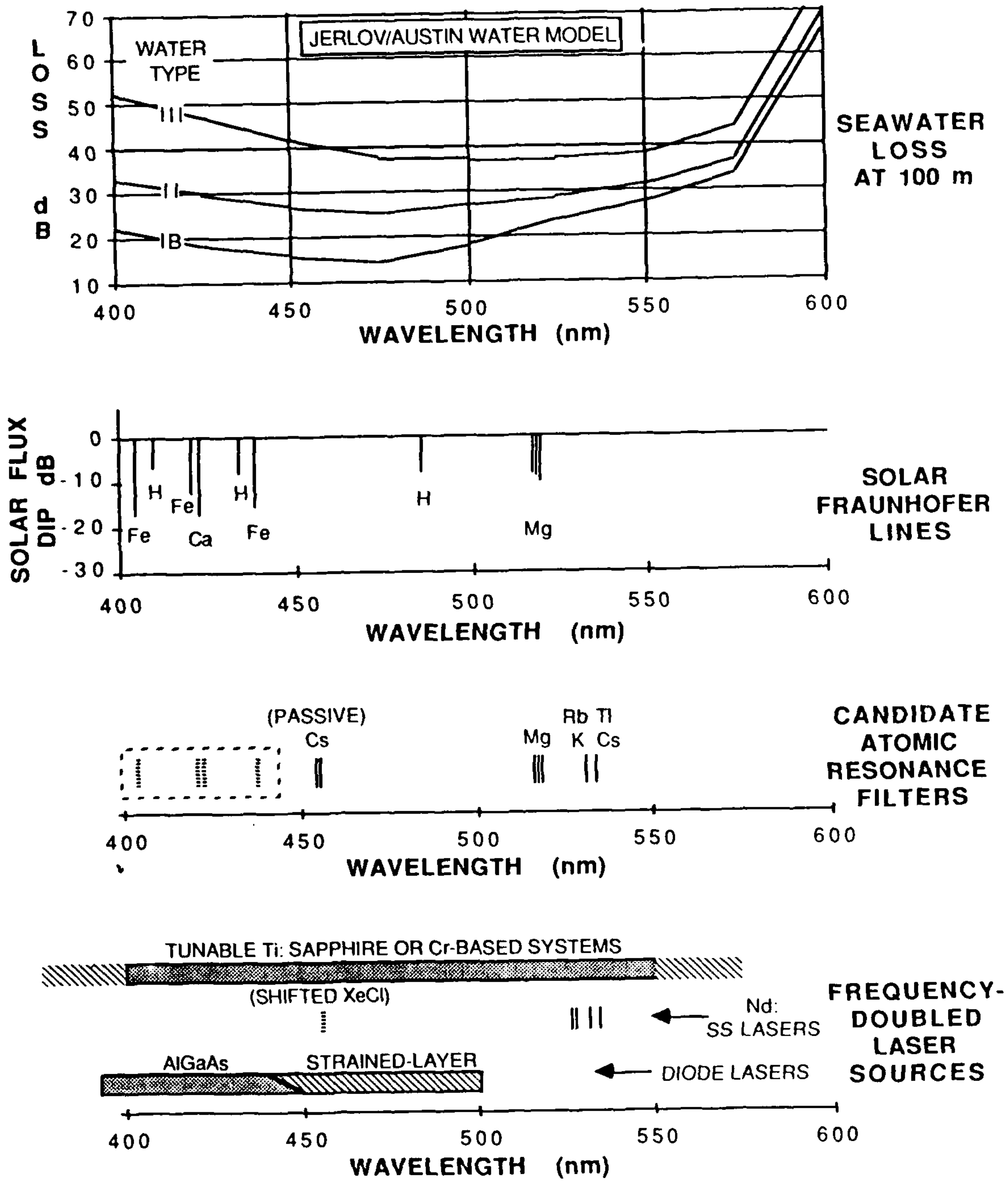
1 Karp, S., R. M. Gagliardi, S. E. Moran and L. B. Stotts, "Optical Channels", Plenum Press New York and London, 1988 pp. 268-269

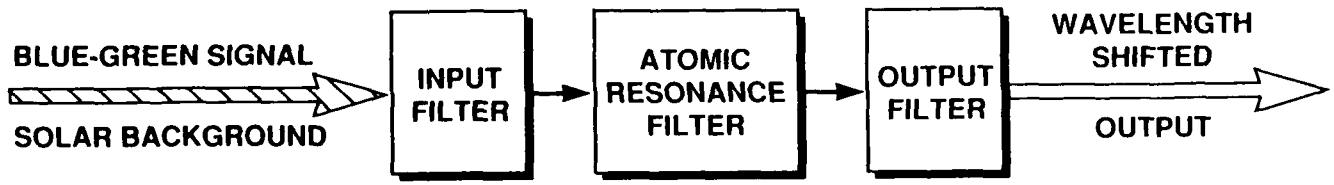
WAVELENGTH ISSUES



The figure illustrates ARF operation and identifies some key implementation concerns. Incoming blue-green signal and solar background light arrives at the filter input from a wide field of view. The ARF element absorbs energy from this incoming light over a *very narrow spectral band and reradiates* this energy at a different (shifted) wavelength. The incident signal energy is then detected by measuring the reradiated light at the shifted wavelength. The exact values of the absorption bandwidth and wavelength shift are determined by the spectroscopic properties of the element used in the ARF. Since all atoms absorb and reradiate at many frequencies, input preselection and output postselection filters must be used in an actual ARF receiver to eliminate nonsignal absorption/reradiation paths which add to the background noise.

RECEIVER SOLAR REJECTION FILTER

- SOLAR BACKGROUND REJECTION FILTER REQUIRED
  - — NARROW BANDWIDTH
  - — WIDE ACCEPTANCE ANGLE
  - — HIGH THROUGHPUT
- CONVENTIONAL FILTERS INADEQUATE
- ATOMIC RESONANCE FILTER (ARF) CAN MEET REQUIREMENTS
  - — BANDWIDTH FROM 1-20 GHz
  - — HEMISPHERICAL ACCEPTANCE ANGLE
  - — HIGH INTERNAL QUANTUM EFFICIENCY



126876-1

An ideal ARF would have the narrowest possible equivalent noise bandwidth, the highest possible signal detection efficiency, and operate at a wavelength where there is low solar background and an efficient transmitter. Both basic physics and technological capabilities force some compromises in the design of a practical ARF.

Atomic Doppler spreads the absorption linewidth to approximately 1 GHz even when there is no additional linewidth broadening from atomic hyperfine structure which produces multiple absorption/reradiation paths at closely space wavelengths. Selecting an atom which does not have hyperfine structure splitting avoids these extra paths which often increase the noise equivalent band width by integer multiples. To assure that the transmitted signal actually passes through the approximate 1 GHz passband, the transmitted wavelength must be carefully controlled and tuned to precompensate for link Doppler.

ARF signal detection efficiency is dependent both upon the internal quantum efficiency of the absorption/reradiation process and upon detector efficiency at the reradiation wavelength. The internal quantum efficiency is determined by the spectroscopic properties of the atom. Present generation detector quantum efficiencies are significantly higher for reradiations shifted upward into the ultraviolet (UV) than for those shifted downward into the infrared. Since energy must be added to produce reradiation in the UV band, all ARFs producing UV emissions must be pumped. Although this pump adds complexity to the receiver, the more efficient signal detection and consequent reduction in transmitter power is likely to produce a less complex system.

Operation with a narrowband ARF at a low background light wavelength, such as a solar Fraunhofer dip, offers the potential of further reducing transmitter size because of the lower background level operating into the equivalent noise bandwidth of the filter. Development of tunable laser sources would allow implementation of a transmitter at the precise wavelength of an ARF selected for bandwidth and wavelength.

DESIRED ARF CHARACTERISTICS

- UTILIZE MINIMUM BANDWIDTH
  - EXPLOIT ATOMIC DOPPLER LINEWIDTH ($\approx$ 1 GHz)
  - USE ATOMIC SYSTEM WITHOUT HYPERFINE STRUCTURE
  - TUNE TRANSMITTER LASER TO REMOVE PLATFORM MOTION DOPPLER
- MAXIMIZE DETECTION EFFICIENCY
  - HIGH INTERNAL QUANTUM EFFICIENCY
  - ACTIVE FILTER WITH UV EMISSION FOR HIGH PMT EFFICIENCY
  - PUMPING REQUIRED
- OPERATE WITHIN SOLAR FRAUNHOFER LINE
  - BACKGROUND REDUCED BY 5-17 dB
  - TUNABLE LASER SOURCE EASES WAVELENGTH MATCHING CONSTRAINT

126881-9

Lincoln Laboratory has researched the spectroscopic properties of a number of elements to identify potential ARFs which would operate at wavelengths which are usable with frequency doubled AlGaAs diode lasers and which are coincident with solar Fraunhofer dips. Several candidate elements have been identified as having the spectroscopic properties necessary for a very narrowband ARF. Each of these candidates has only a single atomic passband and no hyperfine structure splitting to *unnecessarily broaden the effective noise* bandwidth. Each candidate also has reasonable blocking filter constraints and high internal conversion efficiency. All of these candidate ARF materials are for an active ARF in which the reradiated energy is detected in the UV with relatively high efficiency photo cathodes. Thus, each candidate offers the potential of narrow bandwidth and high detection efficiency.

Although several promising candidate ARFs have been identified from atomic spectroscopic properties, experimental development is required to assess their practicality and then to develop an operating ARF from one of the candidates. The potential reduction in SLCSAT transmitter size which could result from the successful development of one of these filters makes such work an attractive investment.

ARF INVESTIGATION RESULTS

- SEVERAL CANDIDATE MATERIALS IDENTIFIED
  - WAVELENGTHS ACCESSIBLE TO DOUBLED AlGaAs LASERS
  - OPERATION WITHIN SOLAR FRAUNHOFER LINE
  - SINGLE ATOMIC PASSBAND FOR LOW NOISE
  - EFFICIENT DETECTION
  - Fe, Ge, Os, Ru, U — ARE CANDIDATE MATERIALS
- EXPERIMENTAL DEVELOPMENT REQUIRED
- LARGE PAYOFF IF SUCCESSFUL

127720-6

The table shows both semiconductor and solid state laser options for SLCSAT transmitters with near and far term efficiency estimates. Since transmitter efficiency determines both prime power and heat dissipation requirements, efficiency is a dominant parameter in determining transmitter satellite size and complexity. The unit outputs shown are for modules designed to achieve power efficient satellite operation. Although these laser technologies allow higher module outputs, a simpler overall spacecraft design is likely to result when modules are no bigger than required to achieve efficient operation. Once efficient module operation is achieved, spatial combining of module outputs on the intended coverage area can produce the equivalent of higher module output. Spatial combining of module outputs for increased output has three advantages over increasing individual module output; namely, (1) spreading waste heat for easier dissipation by the satellite, (2) increasing flexibility for adaption and (3) increasing tolerance of individual module failures. Possible modular implementations of a semiconconductor and a solid state laser transmitter will be discussed later in the presentation. Although there are ongoing laser development programs for each laser technology shown, SLCSAT specific development will be required before using any of these technologies. Necessary SLCSAT specific developments include locking transmitter wavelength to ARF receiver passbands, as well as developing space qualified units, frequency doublers, etc.

SEMICONDUCTOR AND SOLID STATE SOURCES

LASER TYPE (doubled)	WAVELENGTH (nm)	MODULE OUTPUT	EFFICIENCY (elect. to blue)	COMMENTS
DIODE DEVICE				
➡ AlGaAs	390-440	1–5 W peak	15→30 %	• CANDIDATE ARFs IDENTIFIED • RESONANT DOUBLER REQUIRED • FRAUNHOFER LINES ACCESSIBLE
STRAINED-LAYER (GaInAs, GaSbAs)	440-500	"	"	• LASER DEVELOPMENT NEEDED • RESONANT DOUBLER REQUIRED • EXISTING ARF (Cs)
DIODE-PUMPED SS				
Nd:YAG	532		5→15 %	• EXISTING ARFs
➡ Nd:BEL	535			• MATCH PASSBAND OF POOR WATER
➡ Nd:Y_2SiO_5	455, 459	50–200 mJ 10–50 W avg		• SIMPLE DOUBLER • NO FRAUNHOFER LINE
TUNABLE SS				
Ti:SAPPHIRE	400-550	(set by pump and rep rate)	1→5 %	• REQUIRES BLUE PUMP (DOUBLED YAG) • MATCH ANY ARF OR FRAUNHOFER LINE
Cr: HOST ($ScBO_3$, ...)	400-550		5→15 %	• RED PUMP LASER DEVELOPMENT • MATCH ANY ARF OR FRAUNHOFER LINE

(NEAR TERM → FAR TERM PREDICTIONS)

To operate with a minimum bandwidth ARF receiver, a transmitter must be operated in the narrow wavelength band corresponding to the maximum ARF response. Building the transmitter as a master oscillator power amplifier (MOPA) structure permits efficient pulse operation of the high power amplifier stages which are frequency locked to a continuously operating master oscillator laser. The master oscillator must then be tuned to precorrect for signal Doppler. The projected near-term capabilities shown will be used in the system size comparisons.

TRANSMITTER DEVICE PROJECTIONS

- MASTER OSCILLATOR-POWER AMPLIFIER (MOPA) STRUCTURE
  - LASER FREQUENCY OFFSET FROM ABSOLUTE REFERENCE TO PRECORRECT SATELLITE DOPPLER
- NEAR TERM PROJECTIONS OF DEMONSTRATED PERFORMANCE
  - AlGaAs LASER DIODES
    - INJECTION LOCKED ARRAY OR EXTERNAL CAVITY
    - RESONANT DOUBLER
    - BLUE OUTPUT:
      - 1 W PEAK
      - 15% EFFICIENCY (Electrical to Blue)
  - Nd:YAG, Nd:BEL OR Nd:Y_2SiO_5
    - DIODE-PUMPED SOLID STATE ROD OR SLAB
    - SIMPLE DOUBLER
    - BLUE-GREEN OUTPUT:
      - 50 mJ PULSE ENERGY
      - 10-50 W AVERAGE POWER
      - 5% EFFICIENCY (Electrical to Blue)

126881-11

Water losses are a crucial item in SLCSAT sizing calculations. Water propagation loss variations with wavelength, location, depth and time must be accounted for in SLCSAT system designs. Although considerable phenomenological data on optical propagation through sea water is available, these data are rather sparse from a system engineering point of view. Additional measurements, covering a broader range of wavelengths, seasons, times of day, and locations are an essential input to SLCSAT system engineering. There are several widely divergent models for calculating the increase in optical signal attenuation with depth. The system size comparisons in this presentation were calculated using the Austin depth projection of Jerlov surface water losses. Adaptive capabilities engineered into a SLCSAT system to take advantage of variations in cloud cover, channel conditions, etc., can also be used to accommodate refinements in water propagation models as data become available following an initial baseline system design.

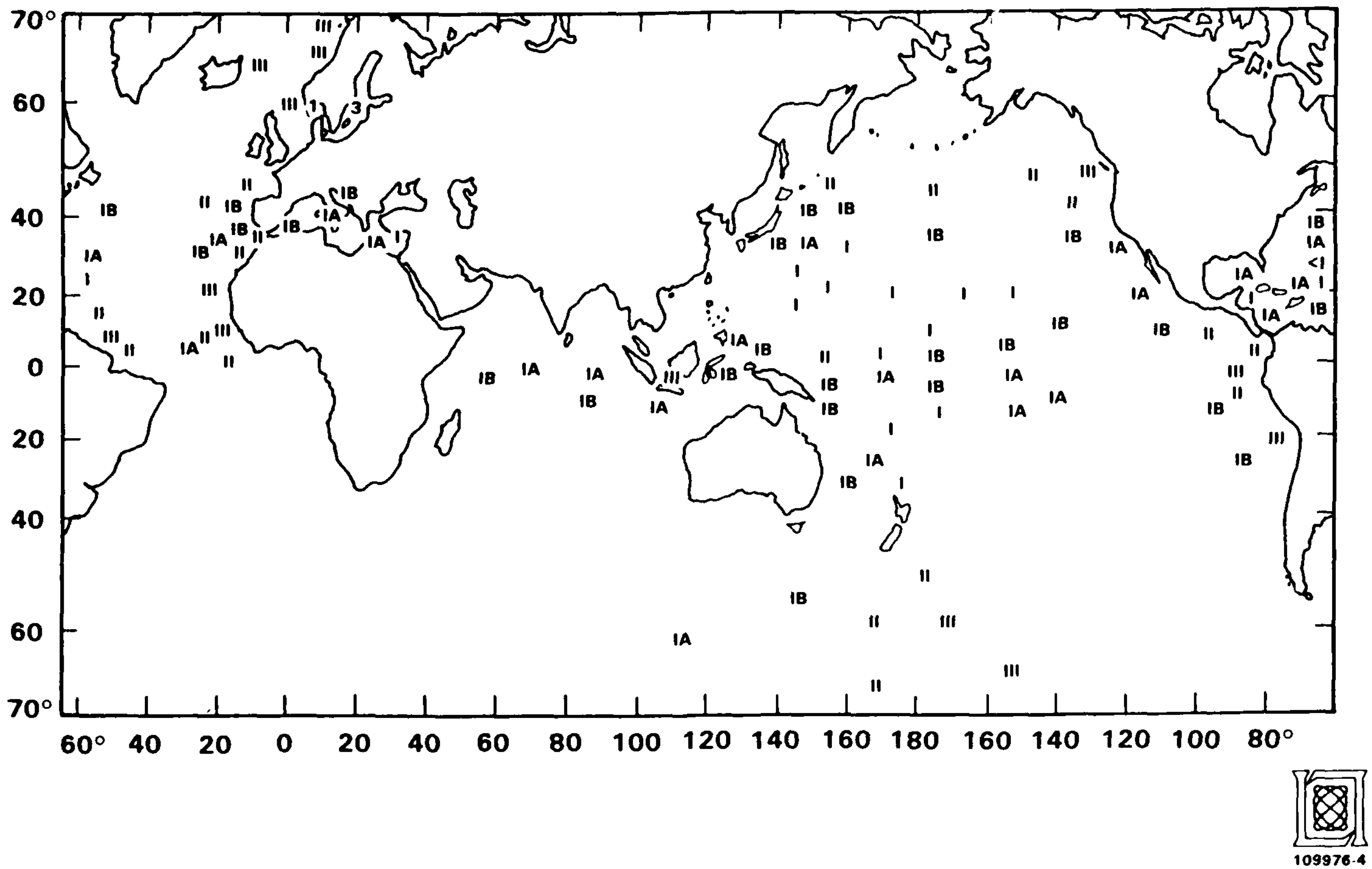
SLCSAT WATER LOSSES

- SIGNIFICANT NATURAL VARIATIONS
  - WAVELENGTH
  - LOCATION
  - DEPTH
  - SEASON, TIME-OF-DAY
- SPARSE MEASURED DATA
- ADDITIONAL MEASUREMENTS HIGHLY DESIRABLE
- DIVERGENCE IN MODELS OF GROWTH OF ATTENUATION WITH DEPTH
  - SURFACE WATER MODEL — VERY CONSERVATIVE
  - NOSC SLCEVAL MODEL — HIGH CLARITY AT DEPTH
  - AUSTIN MODEL — CONSERVATIVE COMPROMISE
- ADAPTIVE SYSTEM DEALS EFFECTIVELY WITH VARIATIONS

126881-13

The range of *optical propagation in seawater* has been coarsely described by Jerlov through the use of several water types to represent conditions in various locations. The system size calculation presented later will show results for Jerlov Types IB, II, and III.

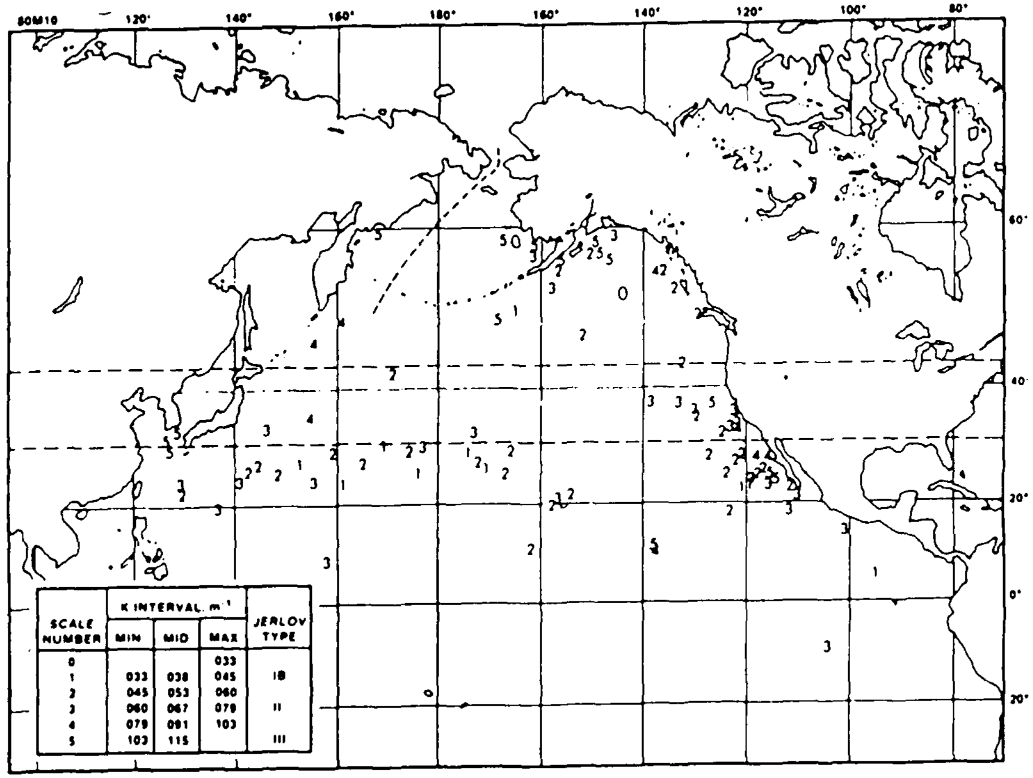
REGIONAL DISTRIBUTION OF OPTICAL WATER TYPES
(From Jerlov)



Additional refinements in seawater modeling have introduced additional resolution both by introducing intermediate water types and by increasing the resolution in the estimates of water type for various areas.

PACIFIC OCEAN DISTRIBUTION OF NEW JERLOV WATER TYPES (All Seasons), 15 JULY 1982

(From Karp, Gagliardi, Moran, Stotts)

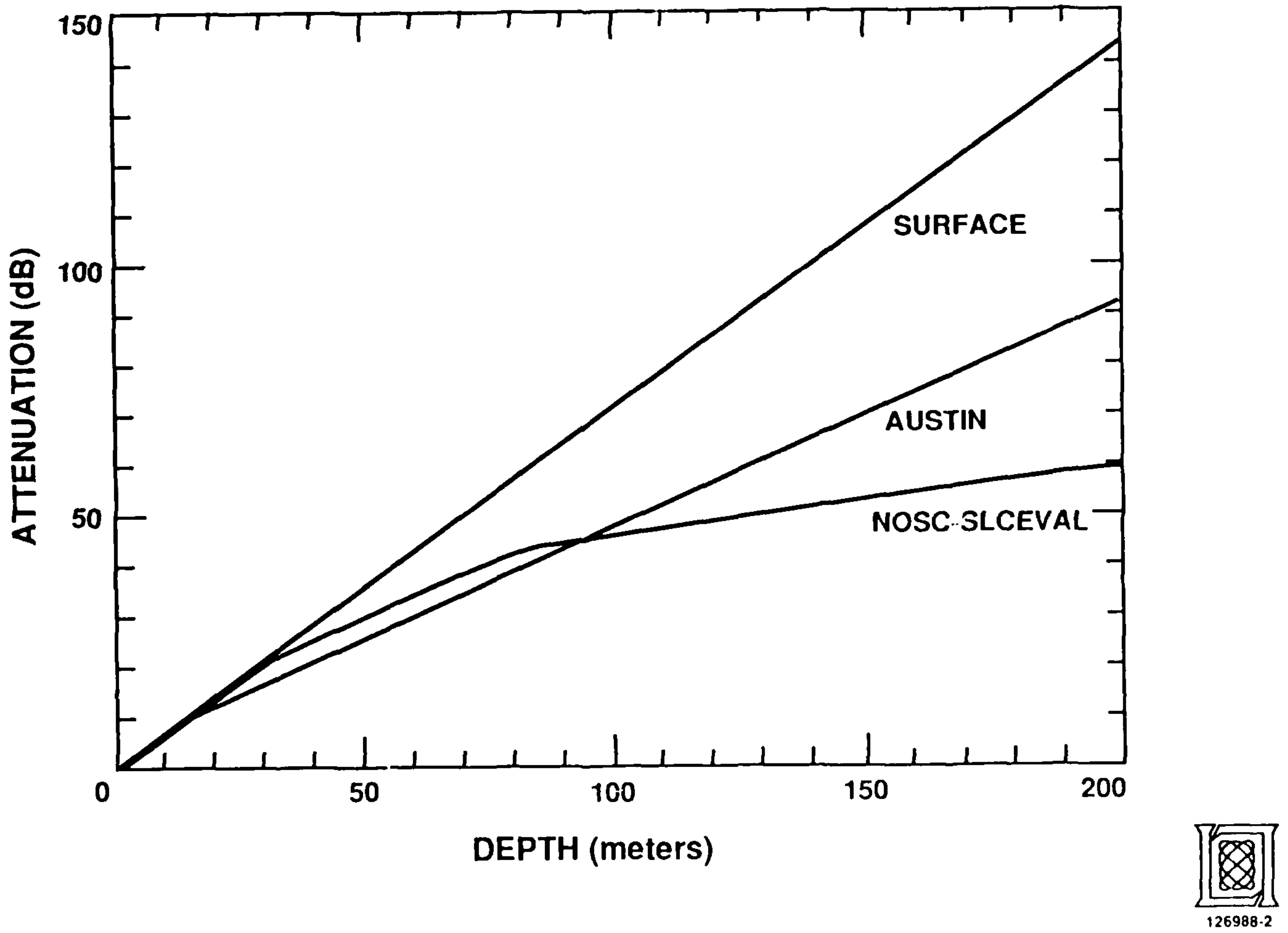


SCALE NUMBER	K INTERVAL, m^{-1}			JERLOV TYPE
	MIN	MID	MAX	
0			033	
1	033	038	045	IB
2	045	053	060	
3	060	067	079	II
4	079	091	103	
5	103	115		III

126881-22

The graph shows the estimated signal attenuation to depth for three different water models. The intermediate Austin model used in the size comparisons presented here appears to be a conservative but realistic compromise between the extremely pessimistic model of projecting surface water loss to depth and the optimistic model of assuming very clear (Jerlov Type IA) water at depths below about 300 feet.

WATER MODEL COMPARISON FOR TYPE III WATER AT 4202 Å



A *common* set of link calculation parameters combined with appropriately chosen modulation and coding parameters must be used to perform a fair comparison of the transmitter power (system size) required to produce a given communication capability with various system designs.

SYSTEM SIZING

- MODULATION/CODING SELECTION
- LINK CALCULATION PARAMETERS
- TRANSMITTER POWER REQUIREMENTS

130806-8

The common link parameters used at all wavelengths for the various technology alternatives are summarized in the table. The -1 dB (80 percent) receiver field of view efficiency requires an ARF-compatible 1-2 steradian field-of-view. The 6 dB signal level margin included in all system size calculations may also be interpreted as a 12 dB margin against additional losses effecting both signal and background; e.g., detector efficiency, optics losses, water losses, etc., or a 12 dB margin against background level increases.

LINCOLN SLCSAT LINK CALCULATION

COMMON PARAMETERS

• WATER LOSSES:	
— WAVELENGTH MODEL	JERLOV
— DEPTH MODEL	AUSTIN
• INSTANTANEOUS TRANSMITTER COVERAGE AREA	10 km DIAMETER
• TRANSMITTER OPTICAL AND PATTERN LOSSES	-2 dB
• RECEIVER FOV EFFICIENCY	-1 dB
• RECEIVER APERTURE	1 SQ METER
• SIGNAL MARGIN	6 dB

(Equivalent to 12 dB Margin Against Noise Level and Channel Losses Common to Signal and Noise)

127184-4

The table shows the transmitter and receiver performance parameters used in comparing systems implemented with three different sets of technological capabilities at the wavelength corresponding to the capability. The ARF noise bandwidths are the minimum *practical bandwidths with no extra* ARF absorption line broadening beyond that required to assure polarization and angle of arrival insensitivity. The extra bandwidth of the Cs ARF is the result of hyperfine splitting which effectively doubles the equivalent noise bandwidth in cesium. The photodetector efficiencies for the Fe and Tl (thallium) ARF's are typical of present generation UV sensitive photomultiplier tubes (PMTs) while the Cs ARF detector efficiency represents a very good present generation infrared PMT.

The 4202 Angstrom Fraunhofer dip has been assumed to suppress the b ickground 12 dB in the 4202 Angstrom calculation. A detailed consideration of the effects of Raman scattering on Fraunhofer dips is under way.

LINCOLN SLCSAT LINK CALCULATION

WAVELENGTH SPECIFIC PARAMETERS

• WAVELENGTH	4202 Å (See Note)	4593 Å	5350 Å
• FRAUNHOFER NOISE DIP	-12 dB	0 dB	0 dB
• TRANSMITTER			
— LASER	AlGaAs	Nd:YSO	Nd:BEL
— EFFICIENCY	15%	5%	5%
• RECEIVER			
— ARF MATERIAL	Fe	Cs	Tl
— ARF NOISE BANDWIDTH	0.010 Å	0.022 Å	0.009 Å
— RECEIVER EFFICIENCY (Net)	9%	1.5%	4.5%
OPTICS	50%	50%	50%
ARF INTRINSIC	60%	60%	30%
PHOTO-DETECTOR	30%	5%	30%

NOTE: SAMPLE FRAUNHOFER LINE/ARF COMBINATION
OTHERS ALSO BEING CONSIDERED

127720-4

The modulation parameters chosen for Nd lasers and for semiconductor lasers were selected to provide the desired baseline capability while accommodating the particular peak/average power trade-offs of each laser technology. The 100 microsecond pulse slots assumed for the Nd laser systems were chosen to be compatible with extreme values of cloud induced multipath time smearing. Given this pulse slot width, 8-ary modulation was chosen to provide adequate data rate while allowing for both coding and adaptation at Kilohertz pulse rates. The Nd system signal format adapts to better channel conditions either by narrowing *the receiver pulse slot width or narrowing* the transmitter and receiver pulse slot while correspondingly increasing the signal alphabet upward from 8-ary. The 250 microsecond pulse slot for the semiconductor laser systems was chosen to achieve substantial immunity from cloud-induced multipath time smearing though the use of symbol times which are long compared to the multipath spread. Given this pulse width, 4-ary modulation was chosen both to provide adequate data rate capabilities and to decrease average transmitter power. The semiconductor laser systems can adapt to less severe multipath conditions by shortening the pulse duration while holding power constant and increasing symbol rate.

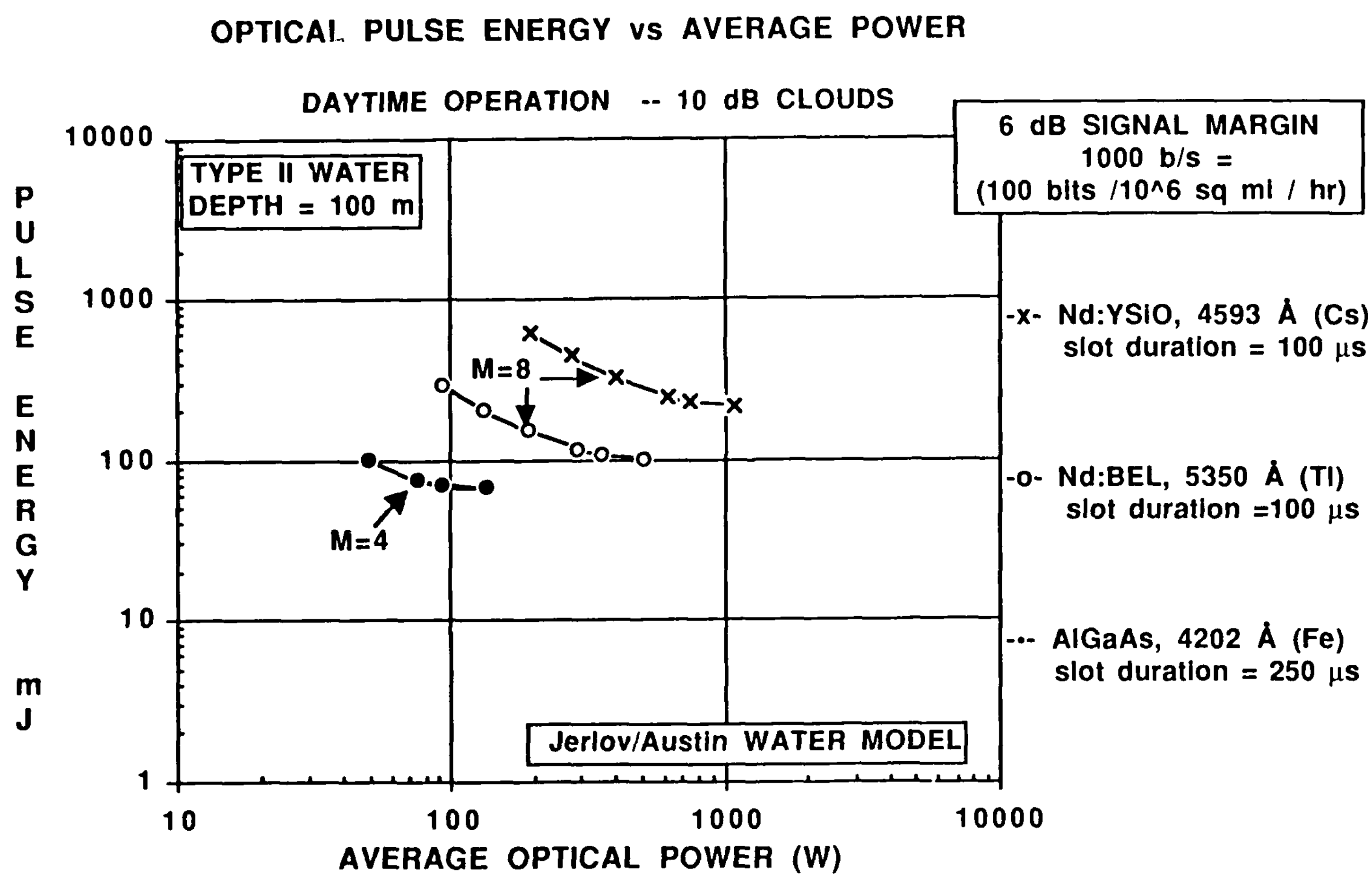
SELECTED MODULATION/CODING MATCHING LASER TRANSMITTERS AND CHANNEL

- SEMICONDUCTOR LASERS:
  - USE CODED 4-ARY PPM FOR GOOD PEAK-POWER/AVERAGE-POWER TRADE-OFF REQUIRING NEAR-MINIMUM NUMBER OF DEVICES
  - CHOOSE 250 μs SIGNAL PULSES TO MITIGATE EFFECTS OF PULSE SPREADING
  - ADAPT BY MODULATING FASTER FOR HIGHER DATA RATES, CHANNEL PERMITTING

- PUMPED SOLID STATE LASER (Nd:XXX):
  - USE CODED M-ARY PPM WITH M CHOSEN TO MATCH MOST EFFECTIVE PULSE REPETITION RATE (1-2 kHz)
  - CHOOSE 8-ARY PPM WITH 100 μs SLOTS
  - RECEIVER CAN ADAPT TO CHANNEL PULSE SPREADING BY NARROWING PULSE GATE
  - USE FINER TIME RESOLUTION (Bigger M) FOR HIGHER DATA RATES, CHANNEL PERMITTING

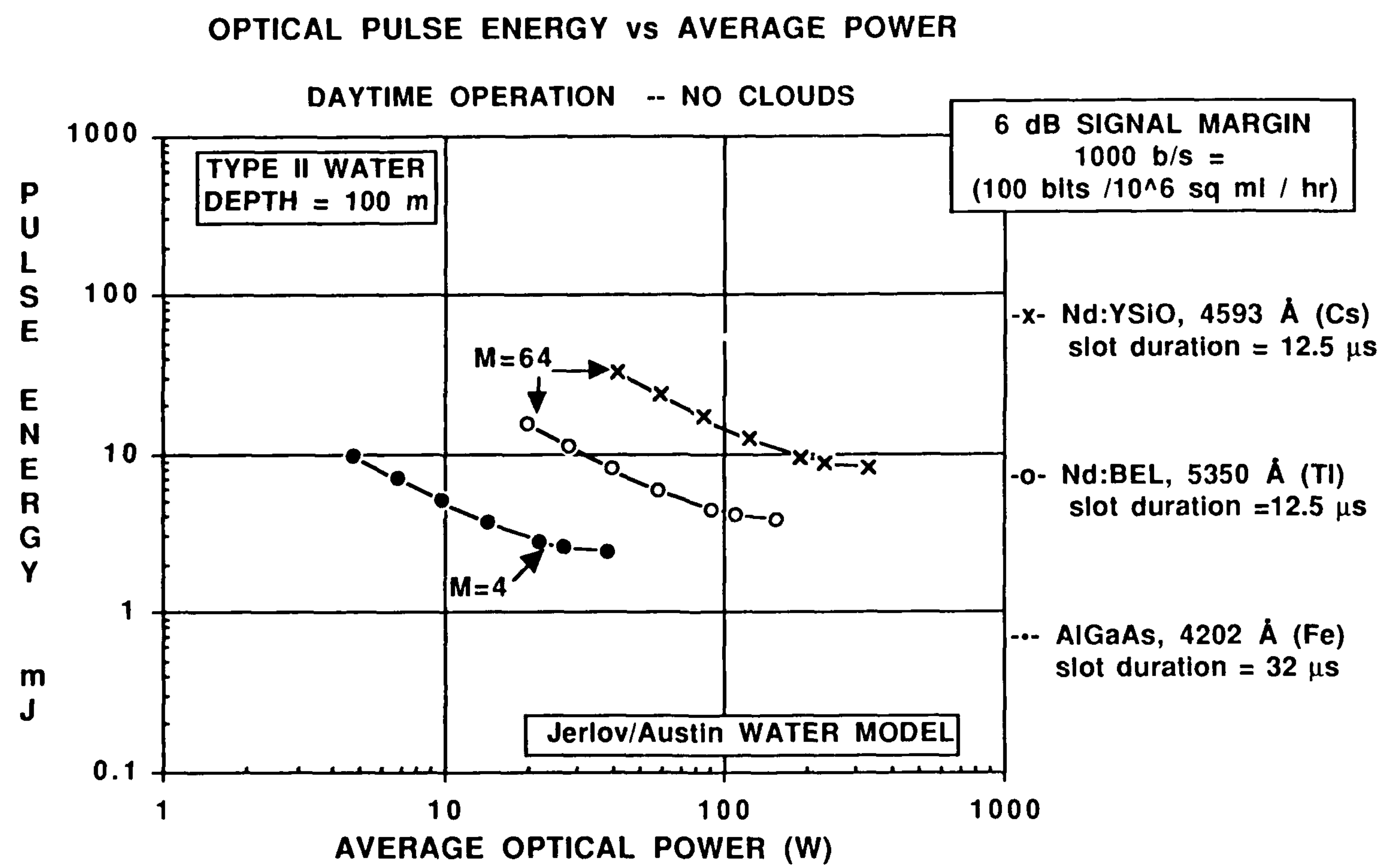
126881-14

The graph illustrates the range of peak power (pulse energy)/average power trade-off for systems providing the reference capability (100 bits to all users in 10^6 square *miles* in one hour) with each technology option. These curves were calculated using the baseline modulation systems operating during a cloudy day with 10 dB cloud loss occurring in both signal and background. The arrows show the values of M used in the system size calculations.

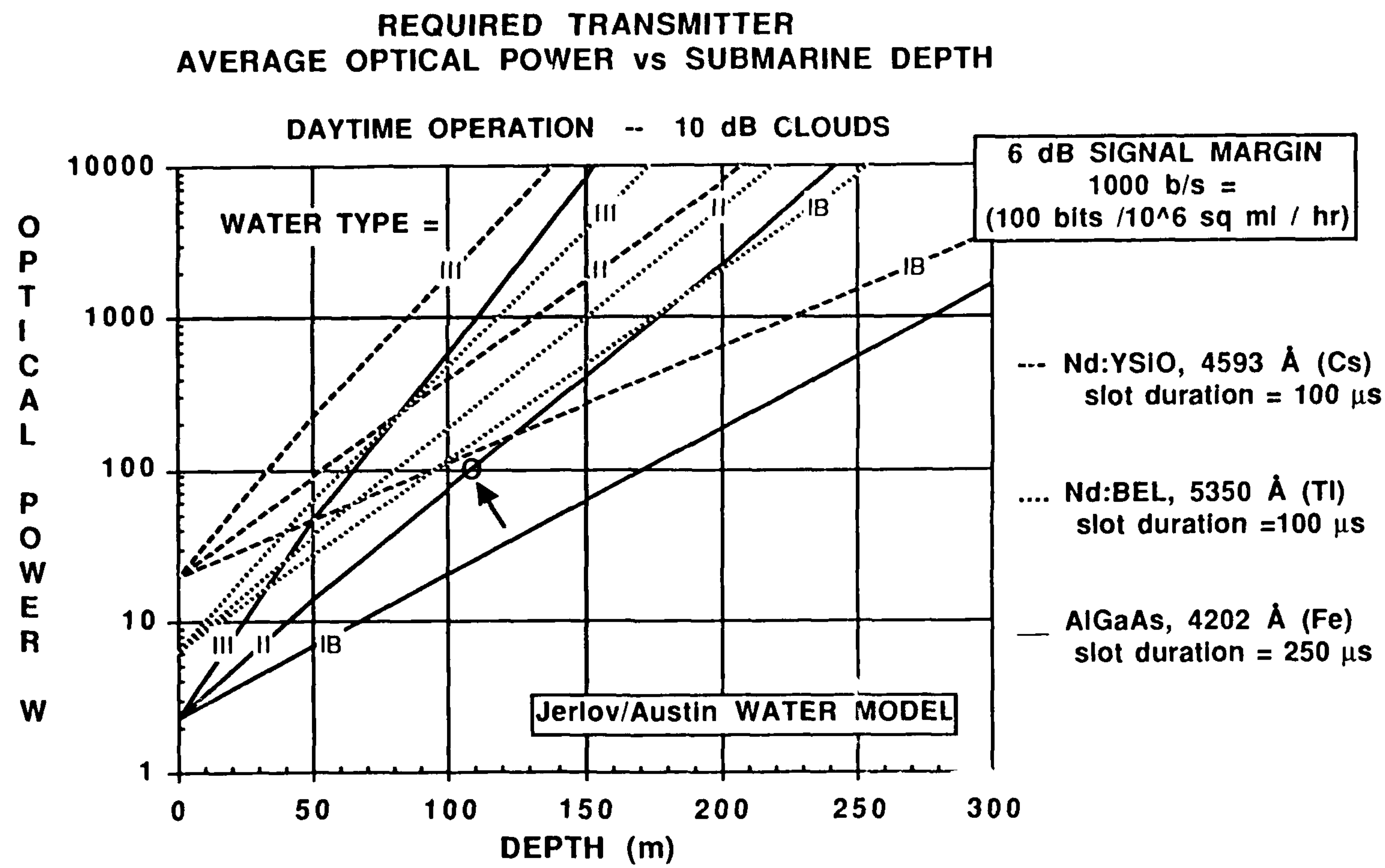


OPTICAL PULSE ENERGY vs AVERAGE POWER
DAYTIME OPERATION -- 10 dB CLOUDS
6 dB SIGNAL MARGIN
1000 b/s =
(100 bits /10^6 sq mi / hr)
TYPE II WATER
DEPTH = 100 m
PULSE ENERGY mJ
10000
1000
100
10
1
M=8
M=4
-x- Nd:YSIO, 4593 Å (Cs)
slot duration = 100 µs
-o- Nd:BEL, 5350 Å (Tl)
slot duration =100 µs
-•- AlGaAs, 4202 Å (Fe)
slot duration = 250 µs
Jerlov/Austin WATER MODEL
10
100
1000
10000
AVERAGE OPTICAL POWER (W)

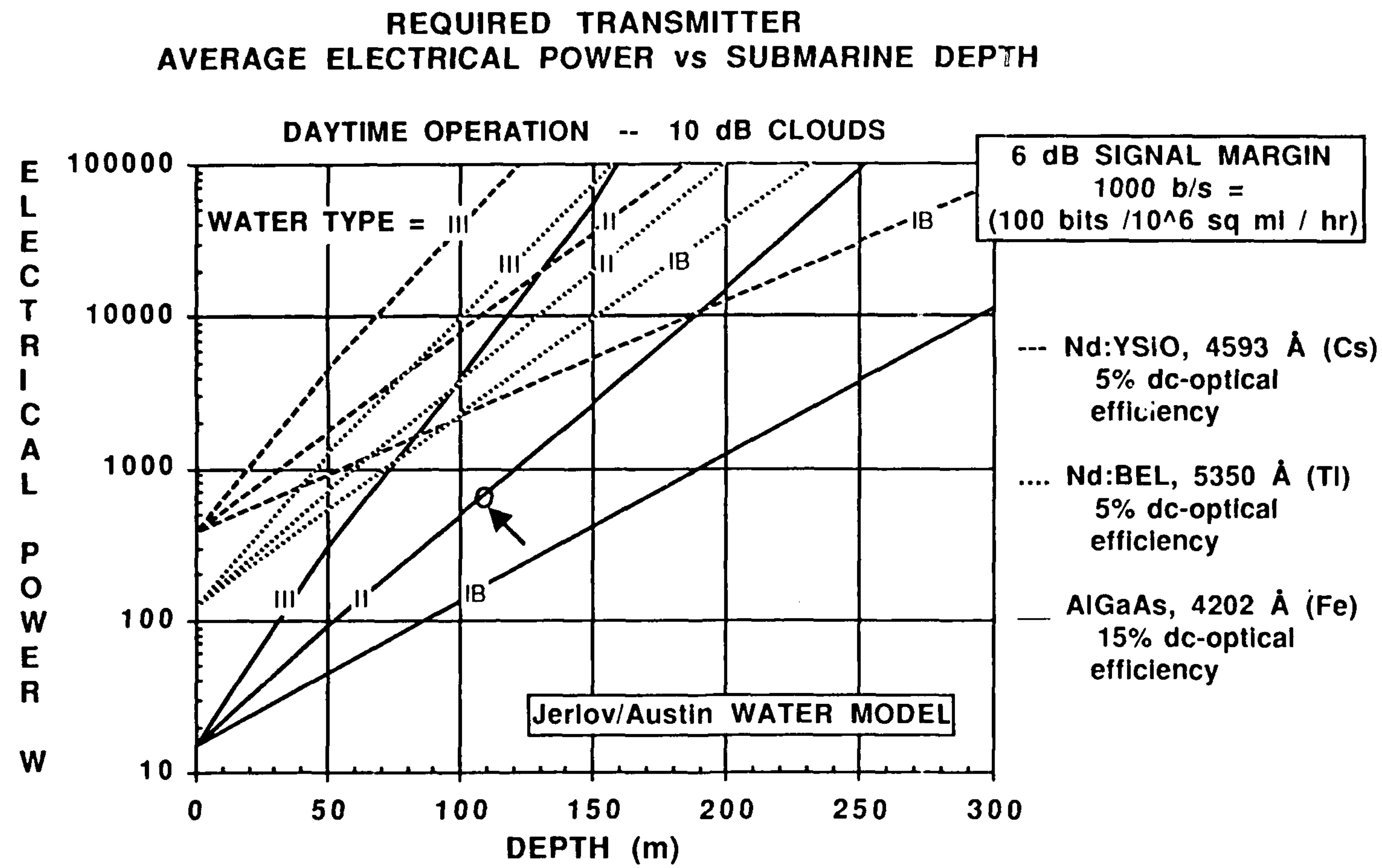
The shorter pulse times which result when the baseline modulation is adapted for clear day operation allow both a wider range peak/average *power trade-offs and* reduced signal power levels. If the transmitter were sized for cloudy conditions, adapting by splitting the transmitter beam into several separate beams (each operating with faster slot times) could speed service to clear areas and thus allow for wide clear area coverage with little decrease in cloudy area coverage.


OPTICAL PULSE ENERGY vs AVERAGE POWER
DAYTIME OPERATION -- NO CLOUDS
6 dB SIGNAL MARGIN
1000 b/s =
(100 bits /10^6 sq mi / hr)
TYPE II WATER
DEPTH = 100 m
PULSE ENERGY mJ
1000
100
10
1
0.1
M=64
M=4
-x- Nd:YSiO, 4593 Å (Cs)
slot duration = 12.5 µs
-o- Nd:BEL, 5350 Å (Tl)
slot duration =12.5 µs
-•- AlGaAs, 4202 Å (Fe)
slot duration = 32 µs
Jerlov/Austin WATER MODEL
1
10
100
1000
AVERAGE OPTICAL POWER (W)

The graph shows the average optical power required to provide the reference capability to various depths in Types IB, II and III water on a cloudy day. The circle at the 100 Watt optical power indicates a benchmark size for the 4202 Angstrom system which will be used in further illustrations of capability trade-offs. The combination of narrowband ARF and Fraunhofer dip background suppression results in a particularly low optical power requirement for a system operating in the 4202 Angstrom Fraunhofer line.


REQUIRED TRANSMITTER
AVERAGE OPTICAL POWER vs SUBMARINE DEPTH
DAYTIME OPERATION -- 10 dB CLOUDS
6 dB SIGNAL MARGIN
1000 b/s =
(100 bits /10^6 sq ml / hr)
WATER TYPE =
III
II
IB
--- Nd:YSIO, 4593 Å (Cs)
slot duration = 100 µs
.... Nd:BEL, 5350 Å (Tl)
slot duration =100 µs
— AlGaAs, 4202 Å (Fe)
slot duration = 250 µs
Jerlov/Austin WATER MODEL
OPTICAL POWER W
10000
1000
100
10
1
0
50
100
150
200
250
300
DEPTH (m)

The advantages of operation with a doubled AlGaAs laser diode transmitter are most apparent in terms of required transmitter input power. The graph shows estimates of the transmitter input power needed to provide the reference capability for the three different technology options. The higher efficiency of the doubled AlGaAs laser diode transmitter translates directly into smaller prime power and cooling requirements and then into correspondingly smaller satellites.



REQUIRED TRANSMITTER
AVERAGE ELECTRICAL POWER vs SUBMARINE DEPTH
DAYTIME OPERATION -- 10 dB CLOUDS
6 dB SIGNAL MARGIN
1000 b/s =
(100 bits /10^6 sq mi / hr)
WATER TYPE = III
III
II
II
IB
IB
III
II
IB
ELECTRICAL POWER W
100000
10000
1000
100
10
0
50
100
150
200
250
300
DEPTH (m)
Jerlov/Austin WATER MODEL
--- Nd:YSIO, 4593 Å (Cs)
5% dc-optical
efficiency
.... Nd:BEL, 5350 Å (Tl)
5% dc-optical
efficiency
— AlGaAs, 4202 Å (Fe)
15% dc-optical
efficiency

The table illustrates the coverage area and depth capabilities which can be achieved through adaptation of a 4202 Angstrom system with a 100 Watt optical power transmitter operating with the previously stated technology and link calculation assumptions including 6 dB signal margin and a 12 dB Fraunhofer dip.

100 WATT BENCHMARK SEMICONDUCTOR SLCSAT SYSTEM

- PERFORMANCE
  - OPERATES IN 4202 Å FRAUNHOFER LINE
  - TRANSMITTER REQUIRES 670 WATTS INPUT POWER
  - 6 dB SIGNAL MARGIN

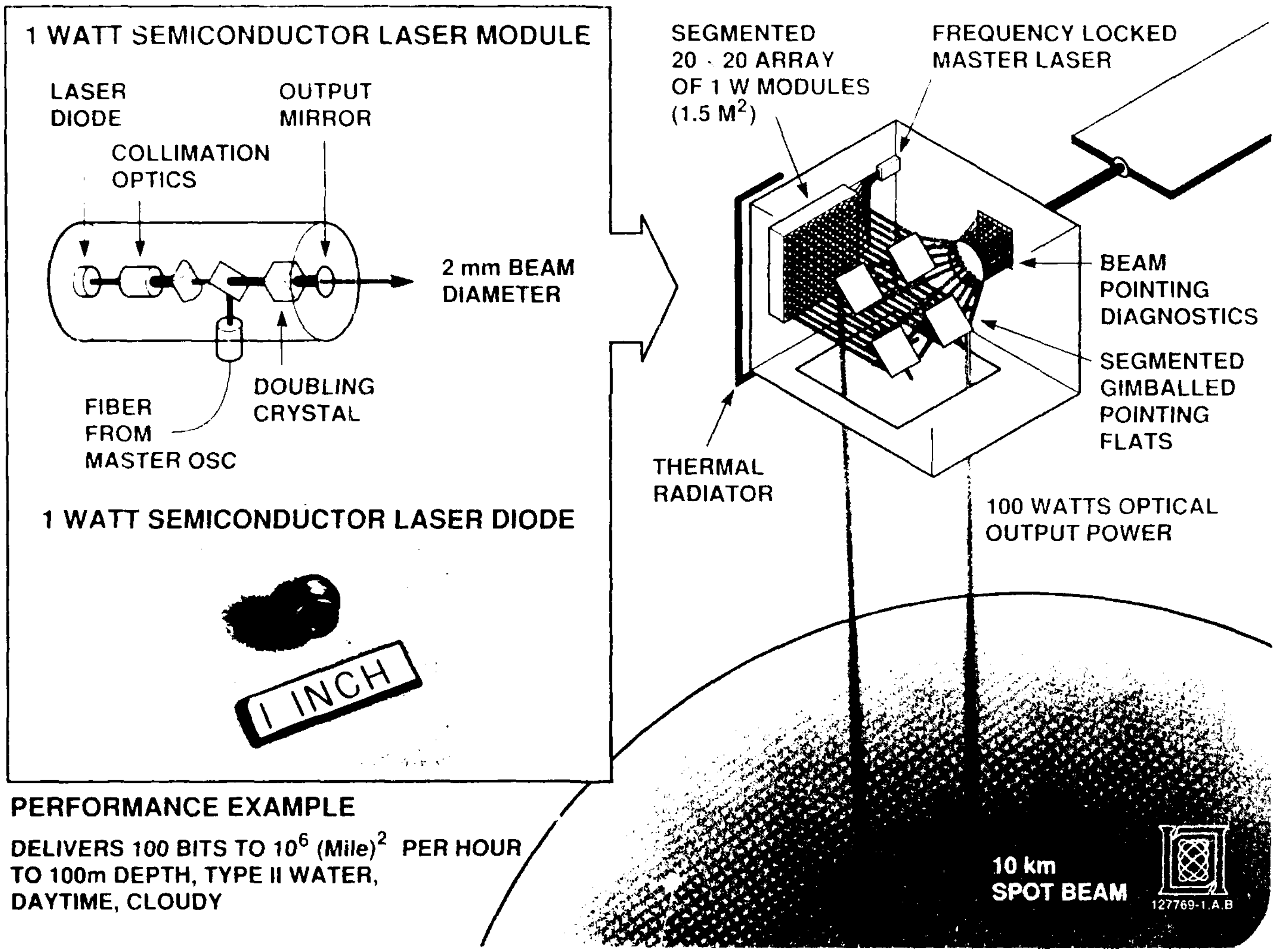
- SAMPLE CAPABILITIES

	AREA COVERAGE TRADE-OFF 100 BITS/HR TO 100 METER DEPTH COVERAGE (Square Miles)		DEPTH TRADE-OFF 100 BITS/HR TO 10^6 SQ MI DEPTH (Meters)	
CONDITION	DAY	NIGHT	DAY	NIGHT
IB CLOUDY	5×10^6	$> 10^7$	170	> 300
II CLOUDY	1.4×10^6	$> 10^7$	110	200
III CLOUDY	3.2×10^4	9×10^6	65	125
IB CLEAR	$> 10^7$	$> 10^7$	220	> 300
II CLEAR	$> 10^7$	$> 10^7$	140	240
III CLEAR	3.2×10^5	$> 10^7$	85	150

127336-10

The figure illustrates a design concept for a SLCSAT transmitter producing 100 Watts of optical power from doubled AlGaAs semiconductor laser diodes. This transmitter system would be built by spatially combining the optical output of 400 modules. Each module would produce 1 Watt of frequency doubled, "blue" peak power while operating at approximately 25 percent duty cycle with 4-ary modulation. Although modules producing frequency locked "blue" light at these signal levels have not yet been developed, semiconductor laser diode arrays have been developed which produce 1 Watt of undoubled power in multiple spatial and temporal modes. Each module would be driven by an optical signal from a frequency stable laser master oscillator pretuned to compensate for link Doppler. Each module would have its own doubling crystal and collimating optics. Since a 2 millimeter diameter beam diverges to only 10 kilometers while propagating from synchronous altitude to the earth's surface, the collimating optics of each module also provide beam shaping and no large telescope is necessary. A number of relatively simple optical pointing flats would steer portions of the total transmitter output power either to separate areas having good channel conditions or to a single area having adverse channel conditions.

SLCSAT TRANSMITTER PACKAGE CONCEPT



PERFORMANCE EXAMPLE

DELIVERS 100 BITS TO 10^6 (Mile)^2 PER HOUR TO 100m DEPTH, TYPE II WATER, DAYTIME, CLOUDY

The table compares some of the basic physical characteristics of AlGaAs semiconductor laser and Nd:BEL solid state laser transmitters sized to provide a comparable SLCSAT communication capability. These two systems were chosen for this comparison since they are the two alternatives requiring the least prime power. The higher optical power required by the Nd:BEL system results from the combination of differences in seawater attenuation and solar background light levels (including the Fraunhofer dip at 4202). The lower electrical to optical power efficiency of the Nd:BEL system further increases its required dc power. The higher power dissipation of the Nd:BEL system further increases transmitter satellite size by increasing the amount of waste heat to be dissipated. The concentration of this waste heat in a small . ume is likely to be a complicating factor in the transmitter thermal design.

The 60 Watt laser diode pump array in each Nd:BEL module would likely be fabricated as a monolithic bar of laser diode arrays similar to those used in each semiconductor laser module. With a basic array producing 1 Watt, each 60 Watt pump array bar would contain 60 arrays for a total of 1200 in the twenty module transmitter system. By comparison, 400 such arrays would be used in the AlGaAs laser transmitter.

The ARF absorption linewidth in either system is sufficiently narrow that the corresponding transmitters would have to be run as amplifiers locked to a stabilized laser oscillator.

127720 8

SLCSAT TRANSMITTER COMPARISON

SIZED FOR 100 BITS TO 10^6 SQUARE MILES/HR, 100 m TYPE II WATER, CLOUDY DAY

	SEMICONDUCTOR (AlGaAs)	SOLID STATE (Nd:BEL)
OPTICAL POWER (Avg) EFFICIENCY (Elec-Optical) ELECTRICAL POWER THERMAL DISSIPATION	100 W 15% 670 W 570 W	200 W 5% 4000 W 3800 W
NUMBER OF MODULES	400 (e.g., 20 × 20 Array)	20
THERMAL CONTROL	DISTRIBUTED THERMAL SOURCE READILY COOLED BY COMMON RADIATOR	CONCENTRATED HIGH HEAT SOURCES MAY REQUIRE LIQUID HEAT TRANSFER TO RADIATOR (190 W/Module)
MODULE DESCRIPTION	2 W AlGaAs DIODE ARRAY DOUBLING CRYSTAL 1 W OUTPUT PEAK	Q-SWITCHED Nd:BEL PULSED PREAMP HIGH POWER DIODE PUMP ARRAY (60 W) Nd:BEL BAR DOUBLING CRYSTAL COOLING 10 W OUTPUT AVERAGE
MASTER OSCILLATOR	TUNABLE AlGaAs LASER	TUNABLE Nd:BEL LASER

This Lincoln Laboratory study of SLCSAT capabilities and size indicates that several advanced technology options, if fully developed, could be incorporated into SLCSAT to reduce substantially system size and complexity. First, the use of signal coding to reduce peak power requirements would allow use of a wider variety of laser transmitter technologies. In particular, such a peak power reduction could allow a SLCSAT to use high efficiency semiconductor diode lasers. Second, signal formats which can be varied to match channel conditions would allow more efficient use of transmitter power. Third, high altitude orbits appear to reduce system complexity in a number of ways without requiring any significant increases in transmitter size or complexity. Finally, a SLCSAT implemented with highly efficient semiconductor or solid state lasers appears to be able to produce a useful communication capability in satellites comparable in size to present on-orbit commercial and military communication satellites.

LINCOLN SLCSAT STUDY CONCLUSIONS

- HIGH ALTITUDE ORBITS PREFERRED FOR CONNECTIVITY AND EASE OF TRANSMITTING SYSTEM DESIGN
- CODING SIGNIFICANTLY REDUCES PEAK POWER REQUIREMENTS MAKING SEMICONDUCTOR SYSTEMS ATTRACTIVE
- ADAPTIVE SIGNAL FORMATS MATCHED TO CHANNEL MAKE MOST EFFICIENT USE OF AVAILABLE TRANSMITTER POWER
- SLCSAT SYSTEMS USING MULTIPLE LOW POWER SEMICONDUCTOR OR SOLID-STATE SOURCES APPEAR TO BE PRACTICAL

127768-1

Two significant tasks must be performed prior to deploying a SLCSAT system such as described above. First, the water channel model, especially for deep water, must be refined and verified though a significant number of systematic propagation measurements. Second, the advanced technologies in the systems described above must be developed and applied to the SLCSAT system. Special emphasis in the development should be placed on ARFs operating in Fraunhofer dips and on semiconductor laser diode transmitters.

LINCOLN SLCSAT STUDY RECOMMENDATIONS

- DEEP WATER CHANNEL MODEL HAS CONSIDERABLE UNCERTAINTY — ADDITIONAL MEASUREMENT PROGRAM RECOMMENDED

- DEVELOP SYSTEM DESIGNS AND TECHNOLOGY USING SEMICONDUCTOR SOURCES AND ARFs MATCHED TO FRAUNHOFER LINES
  - REQUIRE LEAST OPTICAL AND PRIME POWER IN NEARLY ALL CASES
  - SHOULD LEAD TO MOST ECONOMICAL FLIGHT SYSTEM

127336-8

A Lincoln Laboratory program for SLCSAT technology development would address three significant areas. System engineering efforts combined with receiver and transmitter development work would lead to development of an end to end brassboard system demonstrating SLCSAT technology in an environment *where the entire set of system design trade-offs* could be addressed efficiently.

LINCOLN LABORATORY SLCSAT DEVELOPMENT PROGRAM

- SYSTEM ENGINEERING
- DEVELOP HIGH PERFORMANCE RECEIVER
- DEVELOP PRACTICAL TRANSMITTER IMPLEMENTATION
- DEVELOP END-END BRASSBOARD DEMO

126881-15

Lincoln Laboratory system engineering work would concentrate on refining system concepts by incorporating the capabilities and limitations of new technology developments into regularly updated system performance and implementation models. Lincoln's approach to SLCSAT system engineering would be to use Lincoln experience in optical and satellite communication systems to identify areas requiring clarification in an overall SLCSAT system design and technology base to be transferred to Navy contractors as part of system implementation. Jointly conducting this system engineering with technology development at Lincoln, would facilitate the detailed and extensive interaction between system engineering and technology development teams required to quickly incorporate new technology developments into a practical system. A thorough review of water loss models and interaction with seawater propagation specialists is an essential part of any sound system engineering effort. The present proposal clearly identifies the need for such a measurement program before final system design choices are made.

SYSTEM ENGINEERING

- REFINE SYSTEM CONCEPT
  - USER INPUTS
  - EVALUATE SIGNAL DESIGN ALTERNATIVES
    - CODING/MODULATION FORMATS
    - MESSAGE DISTRIBUTION (Beam Combining Scanning)
    - RECEIVER ADAPTATION TECHNIQUE AND CONTROL
    - CHANNEL CONDITION SENSING
  - INCORPORATE TECHNOLOGY DEVELOPMENTS AND REFINEMENTS
- UPDATE SYSTEM SIZING MODELS
  - REVIEW WATER LOSS MEASUREMENTS AND MODELS
  - UPDATE LINK BUDGET
- DEVELOP OVERALL SYSTEM DESIGN
  - SUBSYSTEM IMPLEMENTATION BUDGETS
  - ESTIMATE SPACECRAFT WEIGHT AND POWER

126881-16

The goal of Lincoln SLCSAT receiver development work would be a narrowband ARF receiver operating at a wavelength, especially one matched to a Fraunhofer dip, compatible with efficient semiconductor lasers. Early experimental verification of candidate ARFs identified from spectroscopic properties would be combined with pumping considerations to identify one or more candidate ARFs for further experimental work and development. SLCSAT receiver subsystem design, including collection optics, ARF engineering and adaptive demodulator/decoder design would follow this initial laboratory demonstration.

RECEIVER DEVELOPMENT

- PRELIMINARY SPECTROSCOPIC STUDIES TO NARROW SELECTION OF CANDIDATE MATERIALS FOR ARFs
- DEVELOP ARF PUMPING TECHNIQUE
  - PHOTOLYTIC
  - COLLISIONAL
- BUILD/CHARACTERIZE CANDIDATE ARF(s)
  - NOISE BANDWIDTH, INTRINSIC NOISE
  - QUANTUM EFFICIENCY
- RECEIVER SUBSYSTEM OPTICAL DESIGN
  - COLLECTION OPTICS
  - PRACTICAL ARF
- DEVELOP ADAPTIVE DEMODULATOR/DECODER

126881-17

The goal of Lincoln Laboratory SLCSAT transmitter development would be a doubled semiconductor diode laser transmitter capable of operating with the ARF which would also be developed at Lincoln. Since there are currently extensive commercial and government sponsored efforts to develop multi-Watt AlGaAs laser diode arrays, Lincoln SLCSAT transmitter development would focus on the technologies necessary to incorporate these devices into a SLCSAT transmitter. There are several technologies which must be developed in addition to array technology to allow use of semiconductor diode lasers in a SLCSAT transmitter. Groups in several laboratories are currently working on injection locking AlGaAs laser diode arrays in a master oscillator power amplifier configuration. However, a complete SLCSAT transmitter system will also require a laser master oscillator which can be tuned to precompensate link Doppler and a capability for referencing this oscillator to an on-board absolute wavelength standard. A high-efficiency frequency doubler must also be developed. Transmitter system development will require significant efforts which must be closely coupled to receiver development from the outset. Once these subsystem technologies are developed they will be incorporated into a space-qualifiable module design addressing the full range of spacecraft issues.

TRANSMITTER DEVELOPMENT

- MAXIMALLY UTILIZE COMMERCIALLY AVAILABLE TECHNOLOGY
- AUGMENT ON-GOING HIGH POWER SOURCE DEVELOPMENT
  - ARRAY POWER COMBINING/EXTERNAL CAVITY
  - *MODULATOR* DEVELOPMENT
  - FREQUENCY STANDARD
- HIGH EFFICIENCY DOUBLER DEVELOPMENT
  - RESONANT DOUBLER, MATERIAL/CONFIGURATION SELECTION
- TRANSMITTER MODULE DESIGN
  - OPTO-MECHANICAL, THERMAL, ELECTRICAL
- BEAM SCANNING OPTICS

126881-18

A brassboard demonstration system incorporating these technologies would be developed to permit further refinement of SLCSAT system design while also providing an end-to-end demonstration of key SLCSAT technologies.

BRASSBOARD DEMONSTRATION

- INCORPORATE SUBSYSTEM DEVELOPMENTS
- PROOF OF CONCEPT
- END-TO-END DEMONSTRATION

The staffing of the proposed Lincoln Laboratory SLCSAT development is concentrated in technology and system development for FY90 and FY91 and expands to carry the developed technologies into a SLCSAT transmitter, receiver, and integrated brassboard in FY92 and FY93

LINCOLN SLCSAT DEVELOPMENT SCHEDULE

	FY89	FY90	FY91	FY92	FY93
SYSTEM ENGINEERING		3	3	3	3
FRAUNHOFER LINE ARF DEVELOPMENT		3	3	2	2
HIGH POWER SOURCE DEVELOPMENT		2	3	2	2
TRANSMITTER DEVELOPMENT		1	1	3	3
RECEIVER DEVELOPMENT			1	3	3
BRASSBOARD INTEGRATION				3	3
TOTAL STAFF		9	11	16	16

127317-2

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13. ABSTRACT *(Maximum 200 words)*

This report summarizes the results of a Lincoln Laboratory study of issues affecting Submarine Laser Communication Satellite (SLCSAT) implementation. The study compares alternative SLCSAT downlink implementations using semiconductor and solid-state lasers in terms of the satellite transmitter power required to provide a given level of communication service. Signal coding is applied to increase transmitter design flexibility by accommodating a wider range of peak-to-average power trade-offs. Adaptive signaling structures which allow more efficient use of transmitter optical power in the face of channel variations are illustrated. Receiver atomic resonance filter alternatives compatible with operation in solar Fraunhofer lines are discussed. Power efficient tunable transmitter technologies, particularly frequency doubled AlGaAs diode lasers, are found to be very attractive. SLCSAT system size estimates are presented for the various technologies presented. High leverage SLCSAT technology development areas are identified.

14. SUBJECT TERMS

submarine communication	signal coding	atomic line filters
SLCSAT	adaptive signaling	satellite communication
optical communication	atomic resonance filters	semiconductor diode lasers

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